Highlights from BNL

New Phenomena at RHIC

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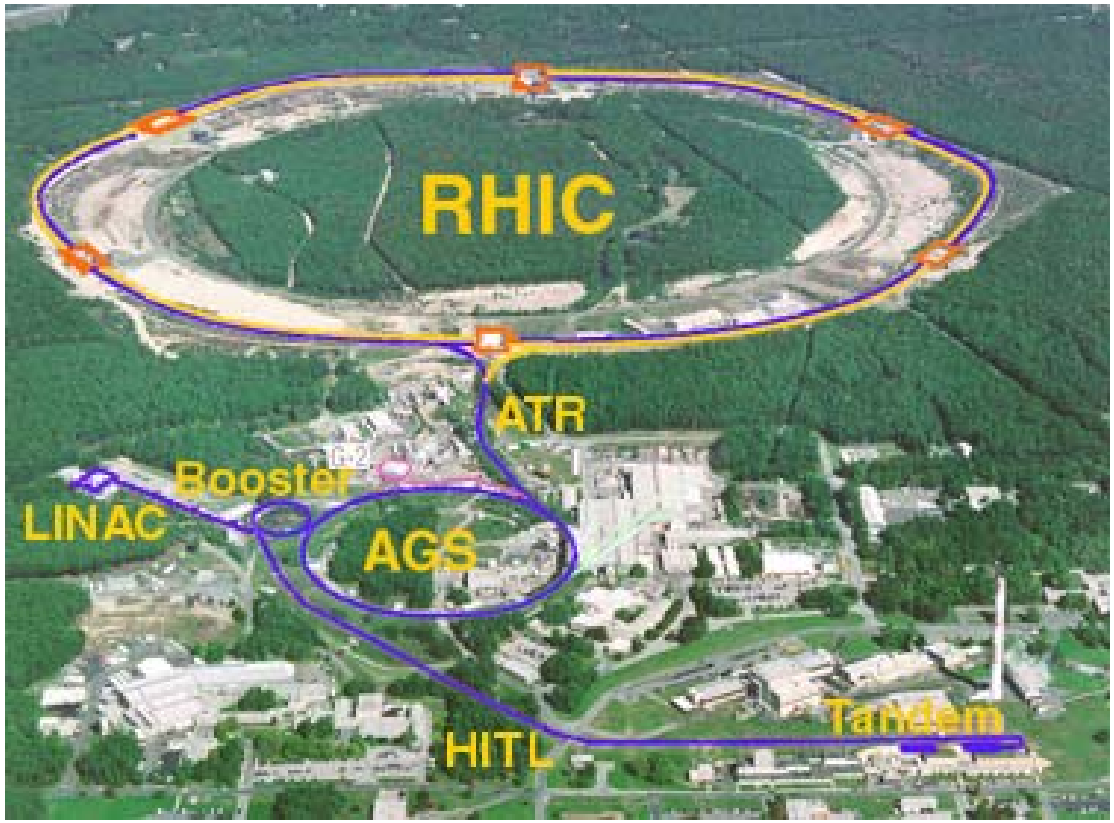
Erice
Aug. 29 – Sept. 7, 2003



BROOKHAVEN
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New forms of matter at RHIC

What are we trying to understand?

What is the behavior of matter at asymptotic energy density?

Quark Gluon Plasma

$\varepsilon \geq 1$ GeV/fm^3

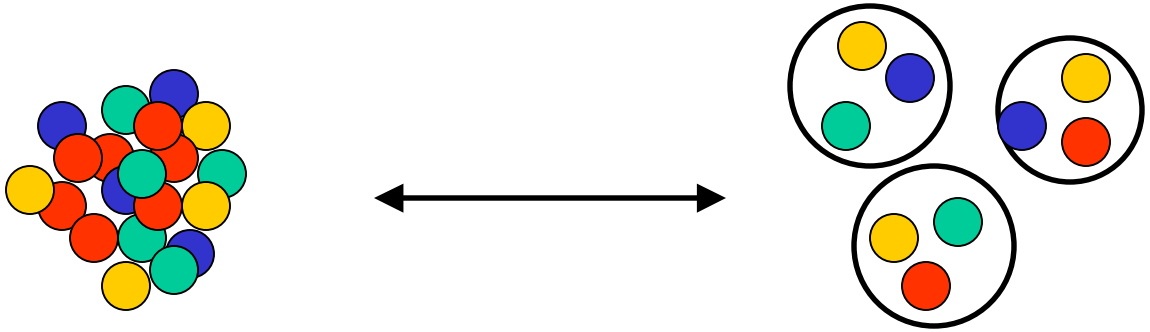
Early universe, neutron stars

Is there a universal initial state of matter in the high energy limit of strong interactions?

Color Glass Condensate

$\rho \geq 1$ GeV/fm^2

The Quark Gluon Plasma

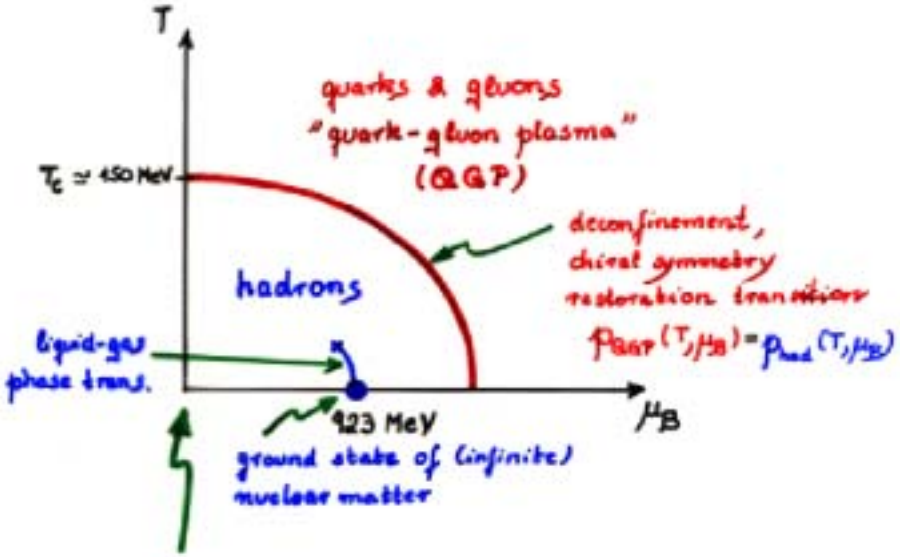


Quark-Gluon Plasma

Hadron Gas

The QCD phase transition:

Critical temperature: 150 – 200 MeV ($\mu_B = 0$)
Critical density: ½ - 2 Baryons/fm^3 (T = 0)
Critical energy density: ~1 GeV/fm^3



What does QCD predict?

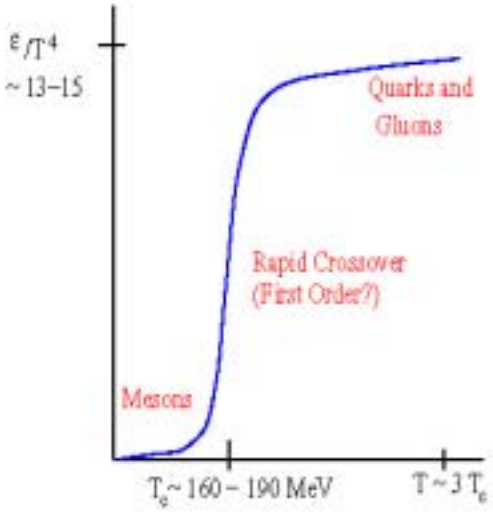
Lattice Gauge Simulations

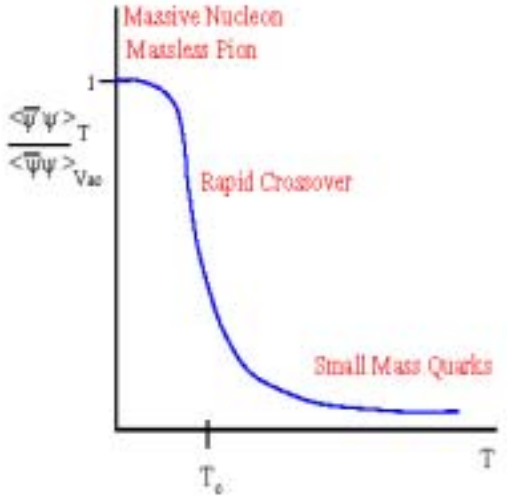
Deconfinement:

N_{dof} changes by
Order of magnitude

Chiral Symmetry:

m_{up}, $m_{down} \approx 0$
$M_{nucleon} \approx 1$ GeV



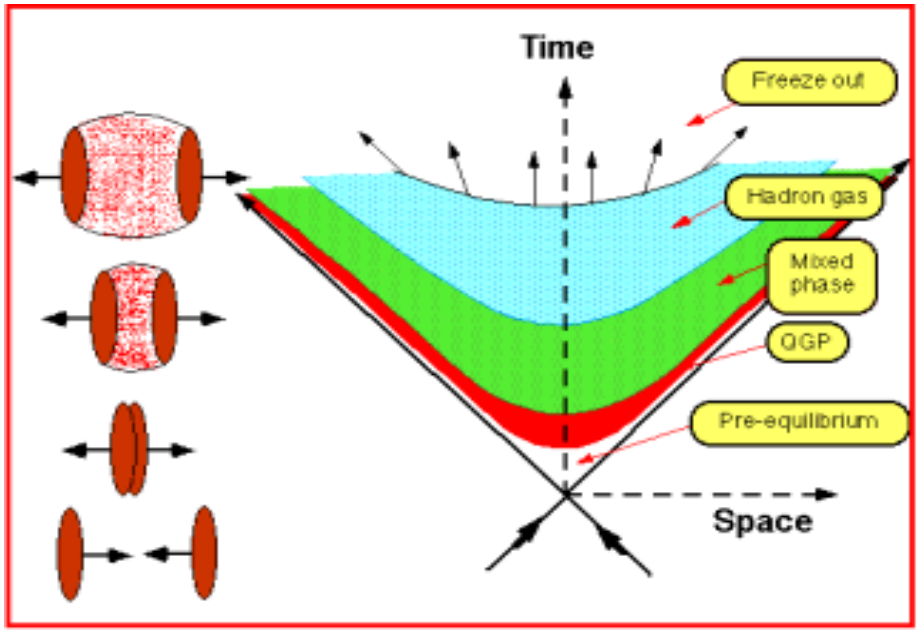


How do particles get their mass?
Are confinement and chiral symmetry related?
What is the equation of state?

A Mini-Bang:

Nuclear matter at extreme temperatures and density

Colliding nuclei at 100 + 100 GeV/nucleon



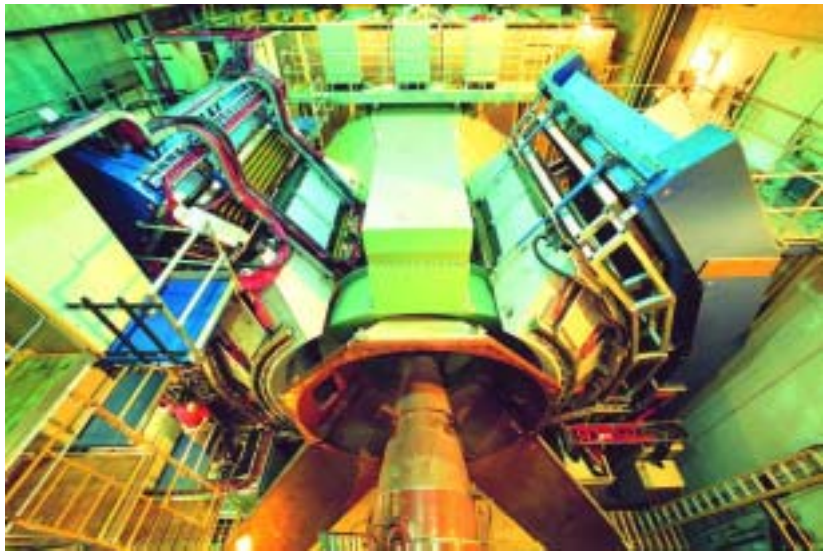
Freeze-out –
emission of hadrons

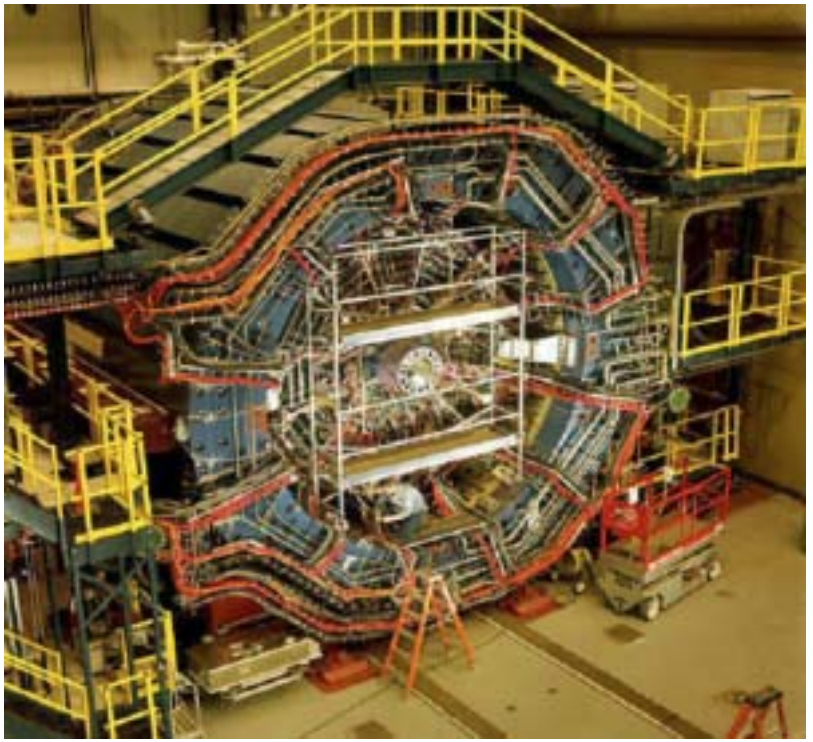
Hot and dense phase -
quark-gluon plasma and hadron gas

Formation phase -
parton scattering

Using heavy ions to excite the QCD vacuum on a large scale

What can we measure?





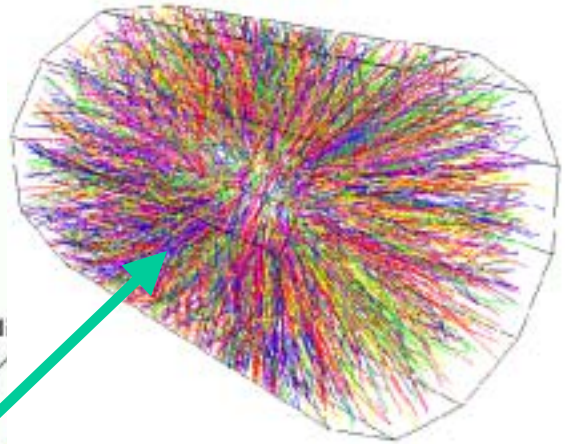
The large RHIC detectors: PHENIX and STAR

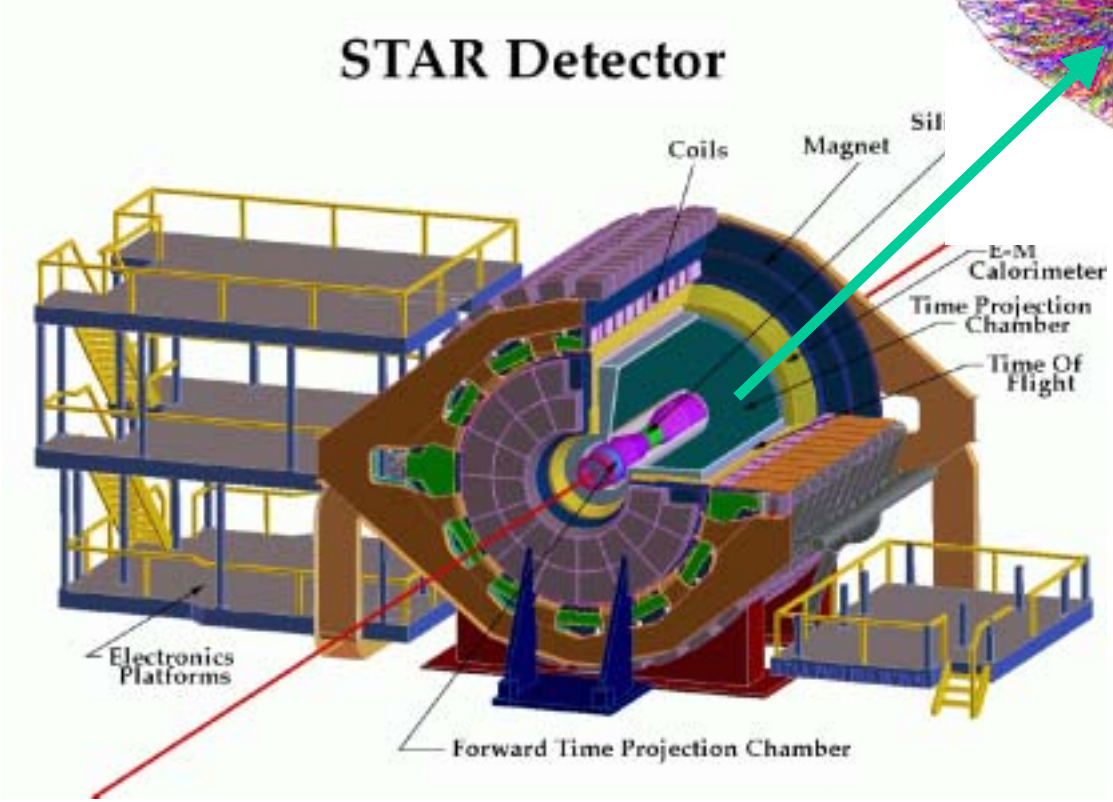
NIM Volume 499 (2003), Nos. 2-3: Special volume on the RHIC Machine and Detectors

STAR : The "Visual" Imaging Detector

- 0.5T Solenoidal Magnet
- Time Projection Chamber…
  - 2m radius x 4m long;
  - 140,000 pad readout x 512 time samples
  - dE/dx in 1 atm. P-10 gas
  - total drift time = 40 μS
- Silicon Vertex Tracker
- Electromagnetic Calorimetry

Central Au-Au collision in the Time Projection Chamber





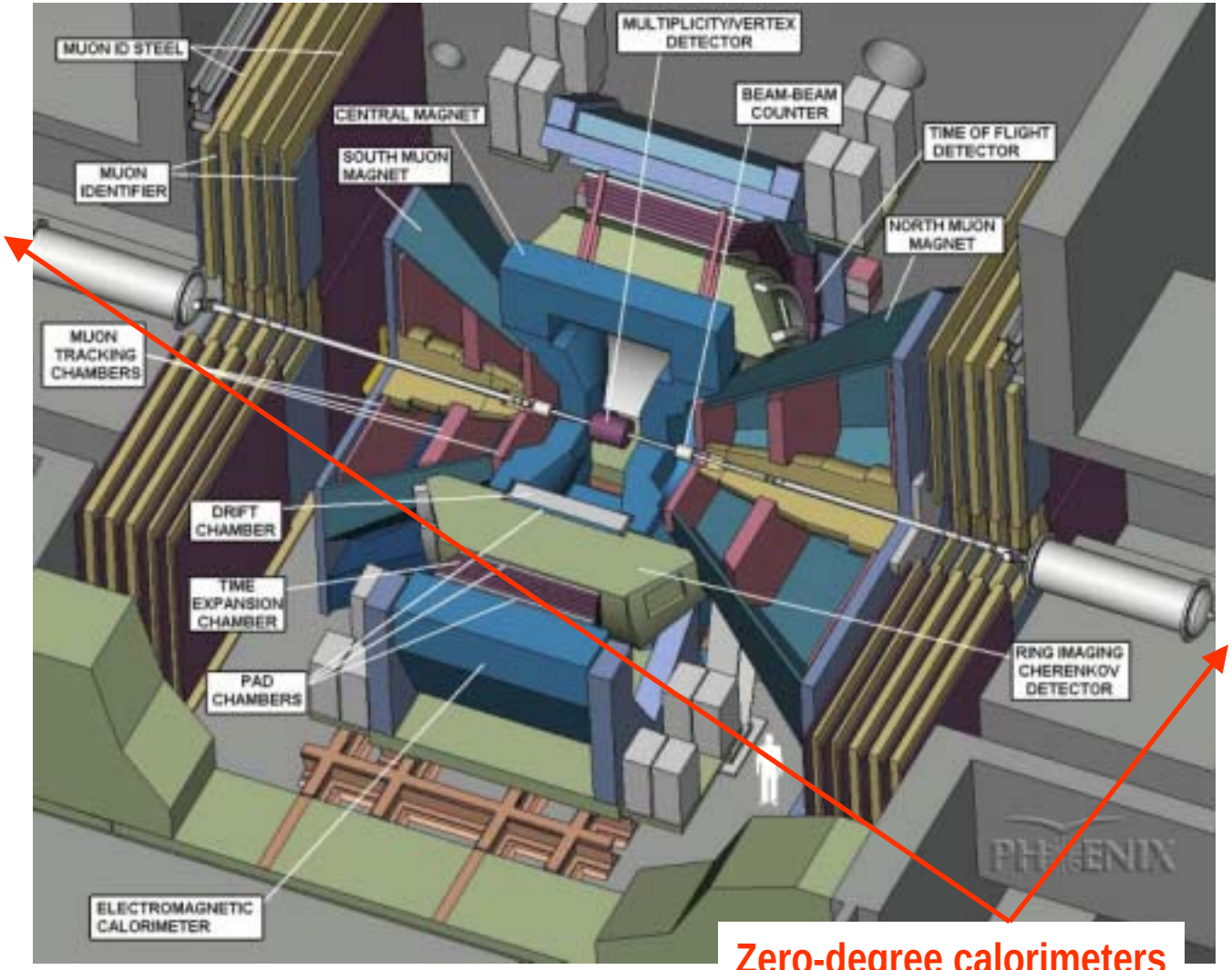
PHENIX Detector

Measure

- **Photons**
- **Electrons**
- **Muons**
- **Hadrons**

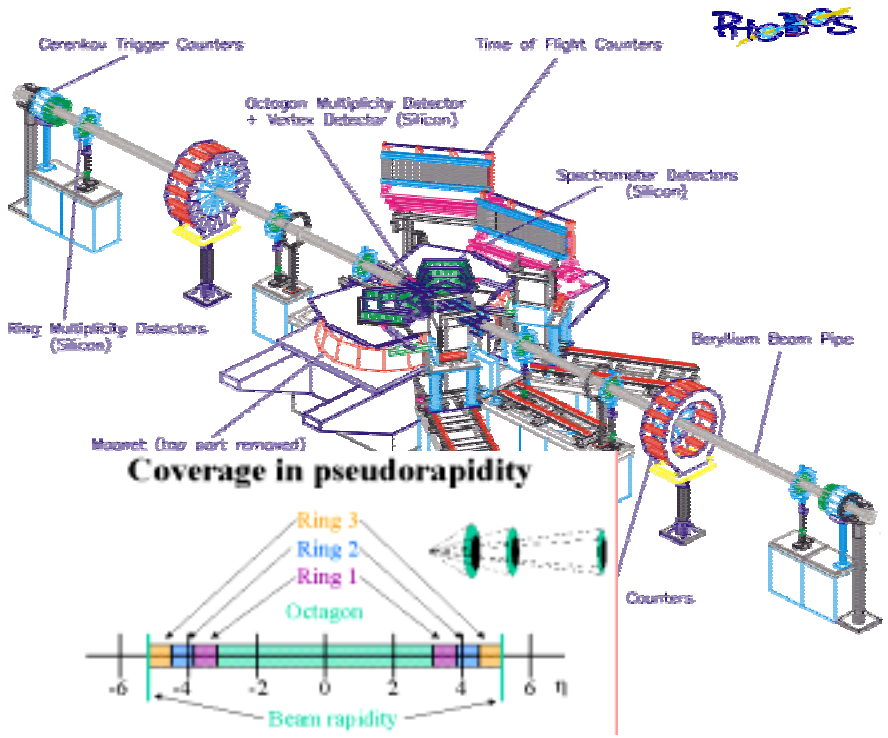
in

- **Two Central Arms**
- **Two Muon Arms**

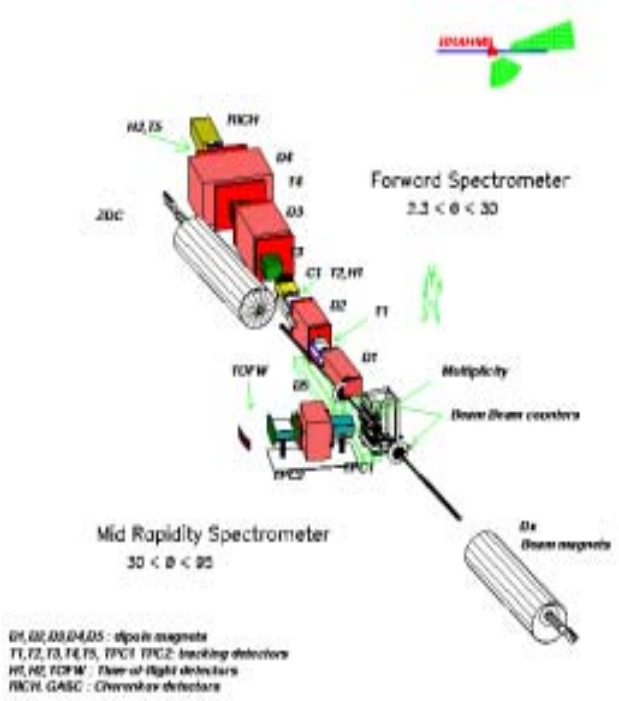


PHOBOS uses silicon Detectors almost exclusively:

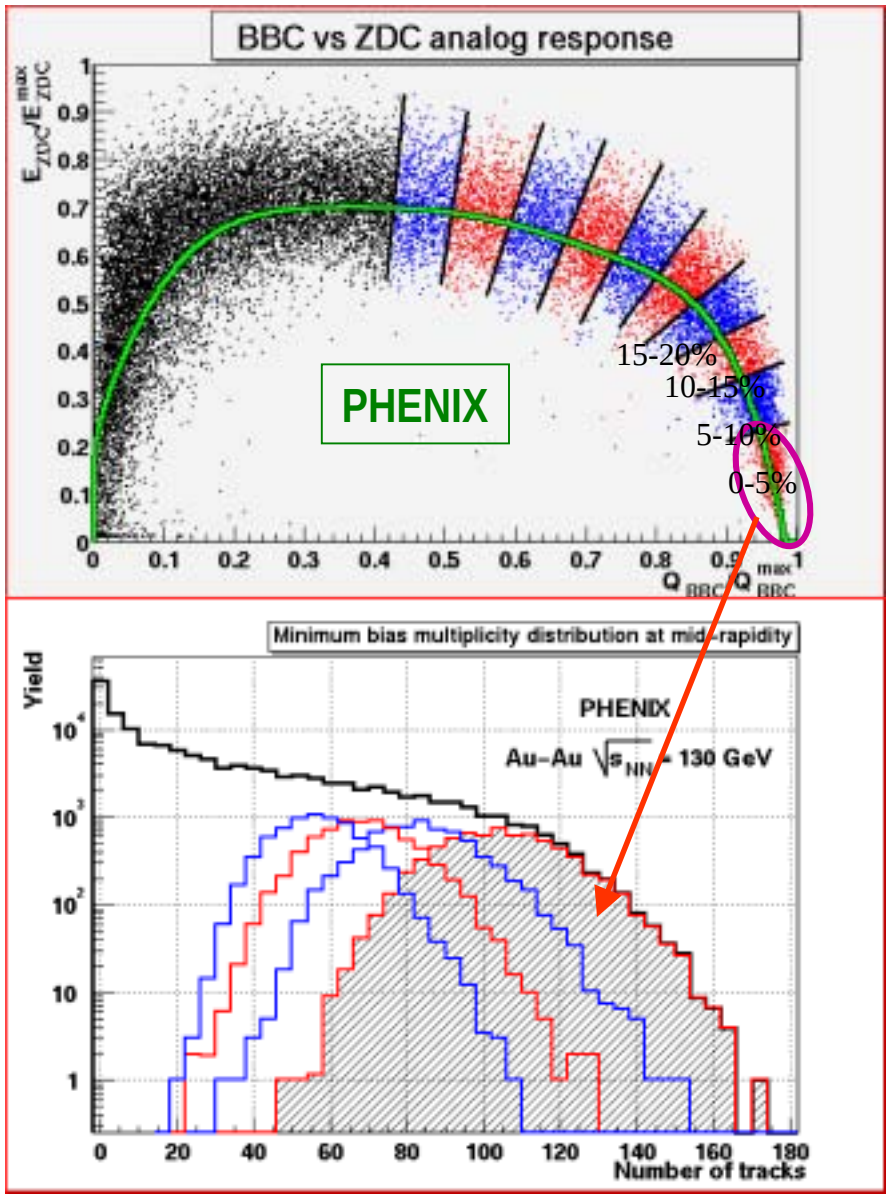
“Rapid response” with ~full coverage in Pseudo-rapidity.

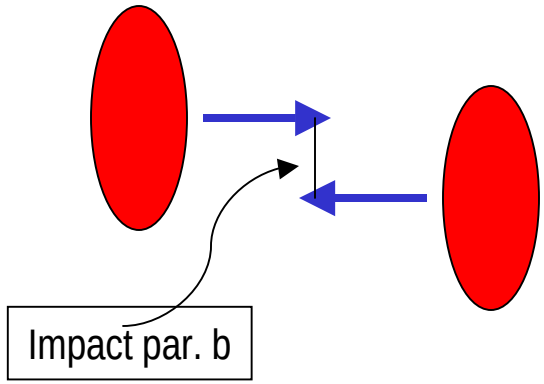


BRAHMS: **Two moveable spectrometer arms sample particles from one set of angles at a time, with high precision over nearly full range of rapidity.**



Geometry of nuclear collisions: Centrality





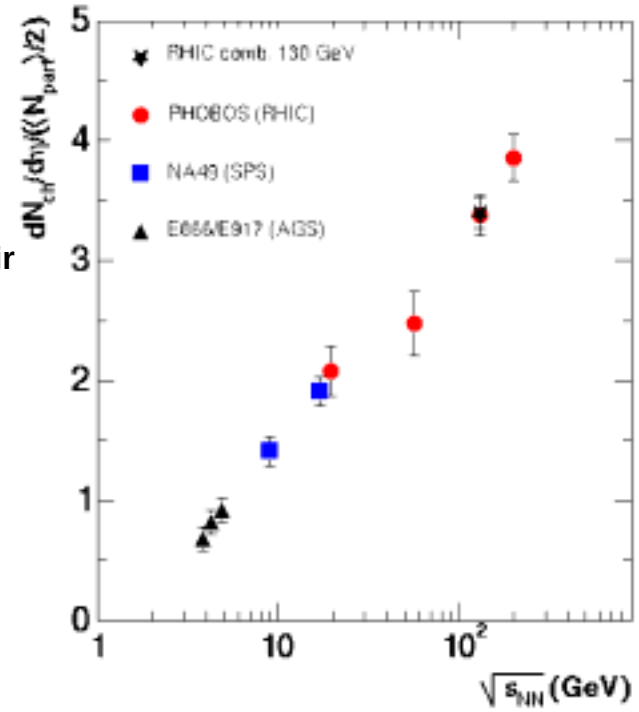
Use combination of
- Zero degree calorimeters
- Beam-Beam counters

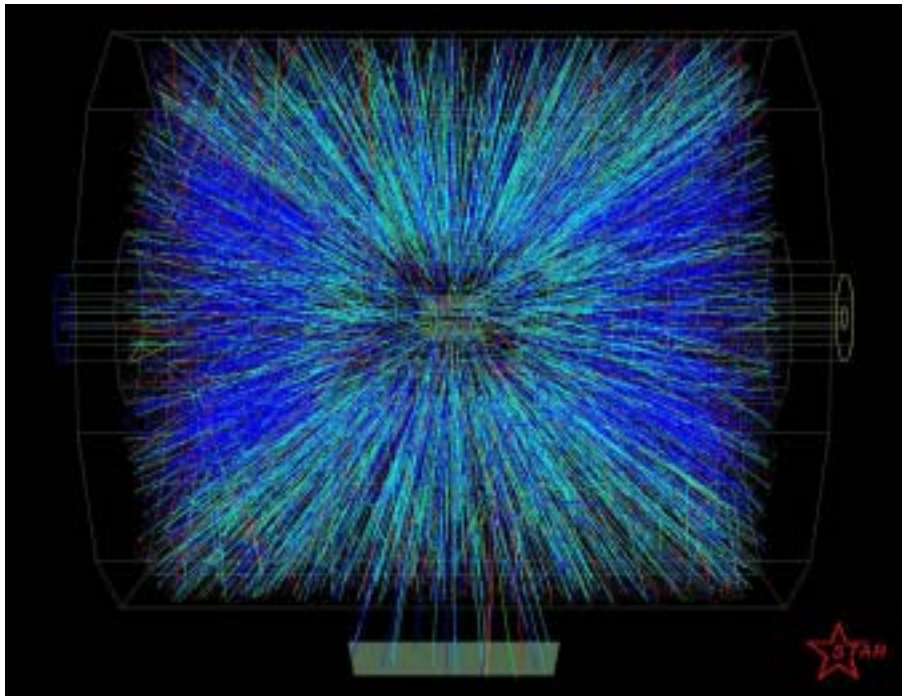
To define centrality classes.

Use Glauber modeling to extract the impact parameter; number of participating nucleons (N_{part}); number of binary collisions (N_{coll}).
These are not directly measurable.

Central Au-Au collision: A Mini-Bang?

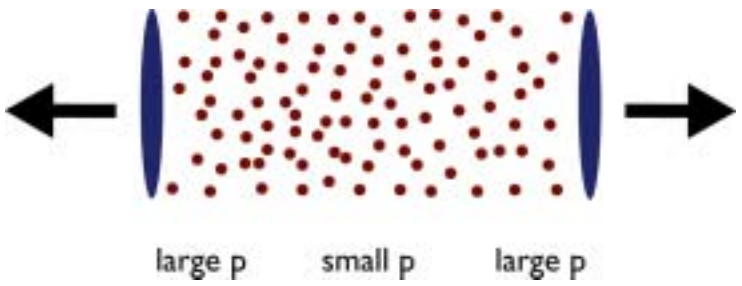
Charged paricle multiplicity density per interacting nucleon pair



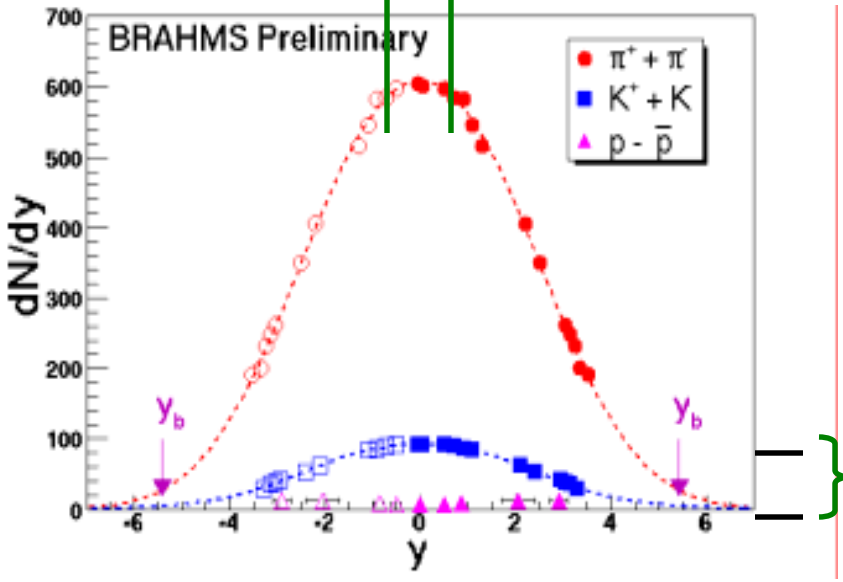


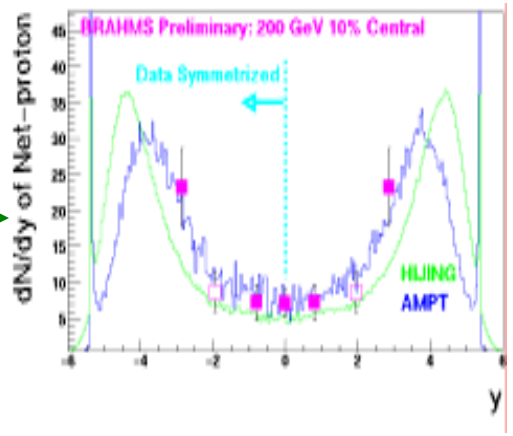
Initial energy density >10 GeV/fm^3 over a volume of ~1000 fm^3

Anatomy of a [central] RHIC collision



Initial Energy Density:
ε_0 = 5 – 30 GeV/fm^3



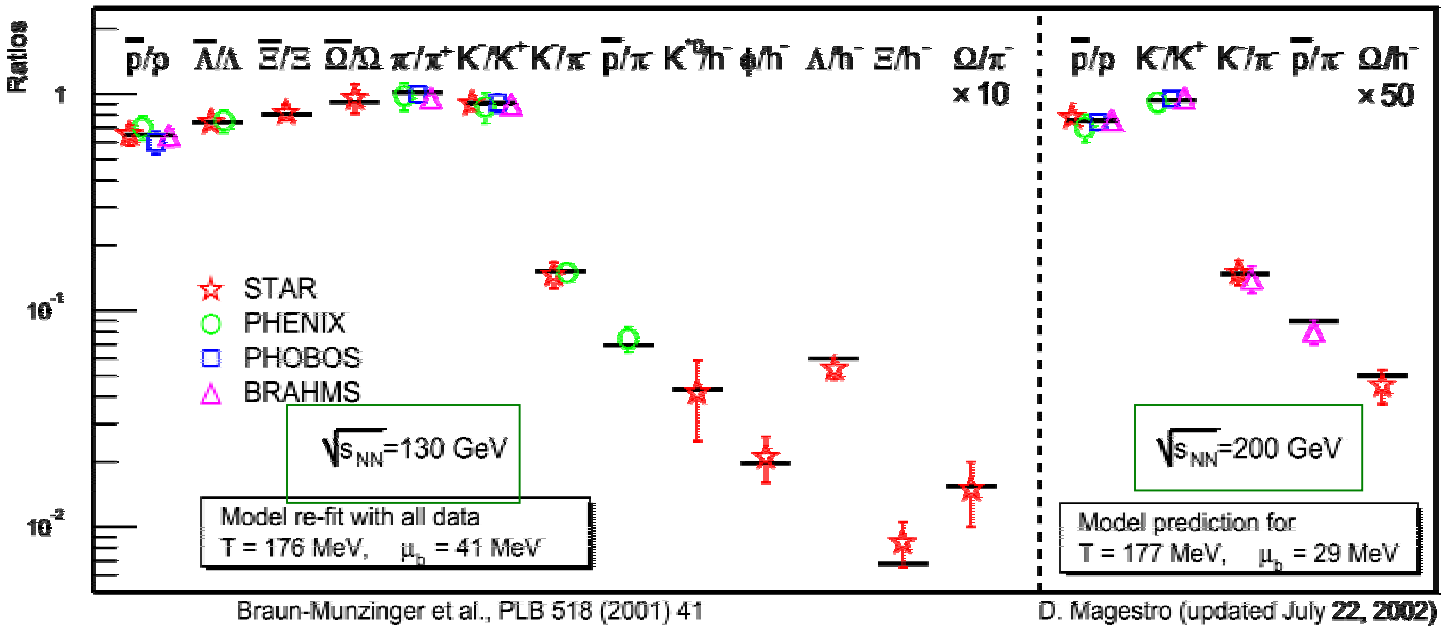


Near-zero baryon density at mid-rapidity:

Net baryons ~1% of particle density.

¾ of observed protons are from pair prod.

Surveying the landscape at “freeze-out”



Braun-Munzinger et al., PLB 518 (2001) 41

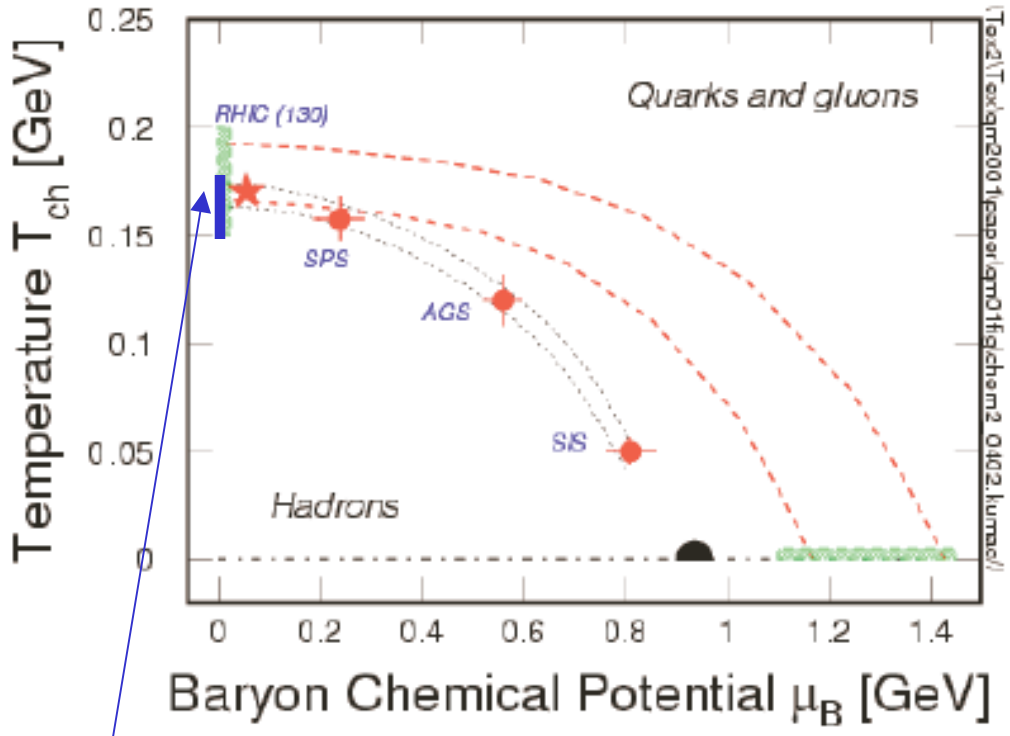
D. Magestro (updated July 22, 2002)

Particle abundance ratios fit to thermal model:

Temperature ~177 MeV: $\approx T_C$ from lattice QCD calculations

Baryon chemical potential approaching zero

Thermodynamics of strong matter

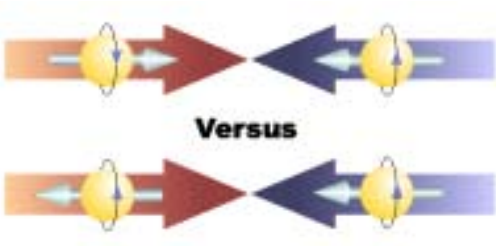


- It's hot enough…
- It's dense enough…
- Is it "matter" (thermal)?
- Is it "quark matter" (partons in thermal equilibrium)?

Lattice QCD calculations: $T_{critical}$ ~ 150 – 180 MeV

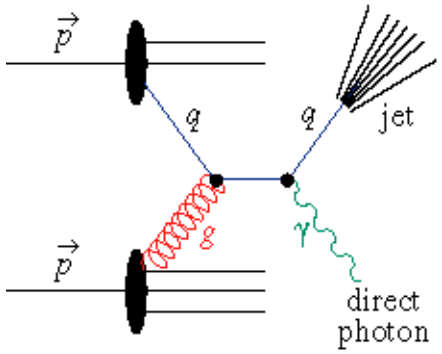
See F. Karsch, Nucl. Phys. A698, 199c

Spin at RHIC



High Energy collisions of polarized protons:

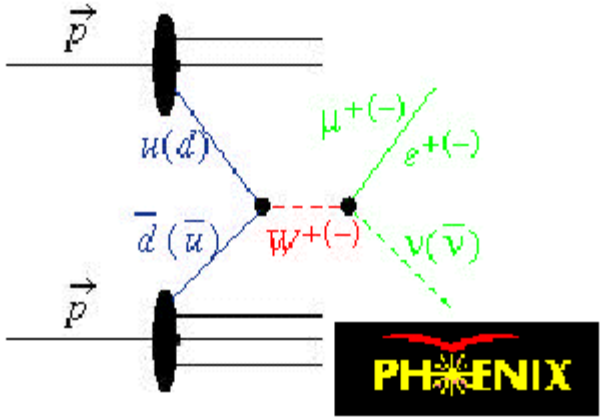
- **Measure the gluon contribution to the spin of the nucleon.**
- **Flavor decomposition of the proton's spin.**



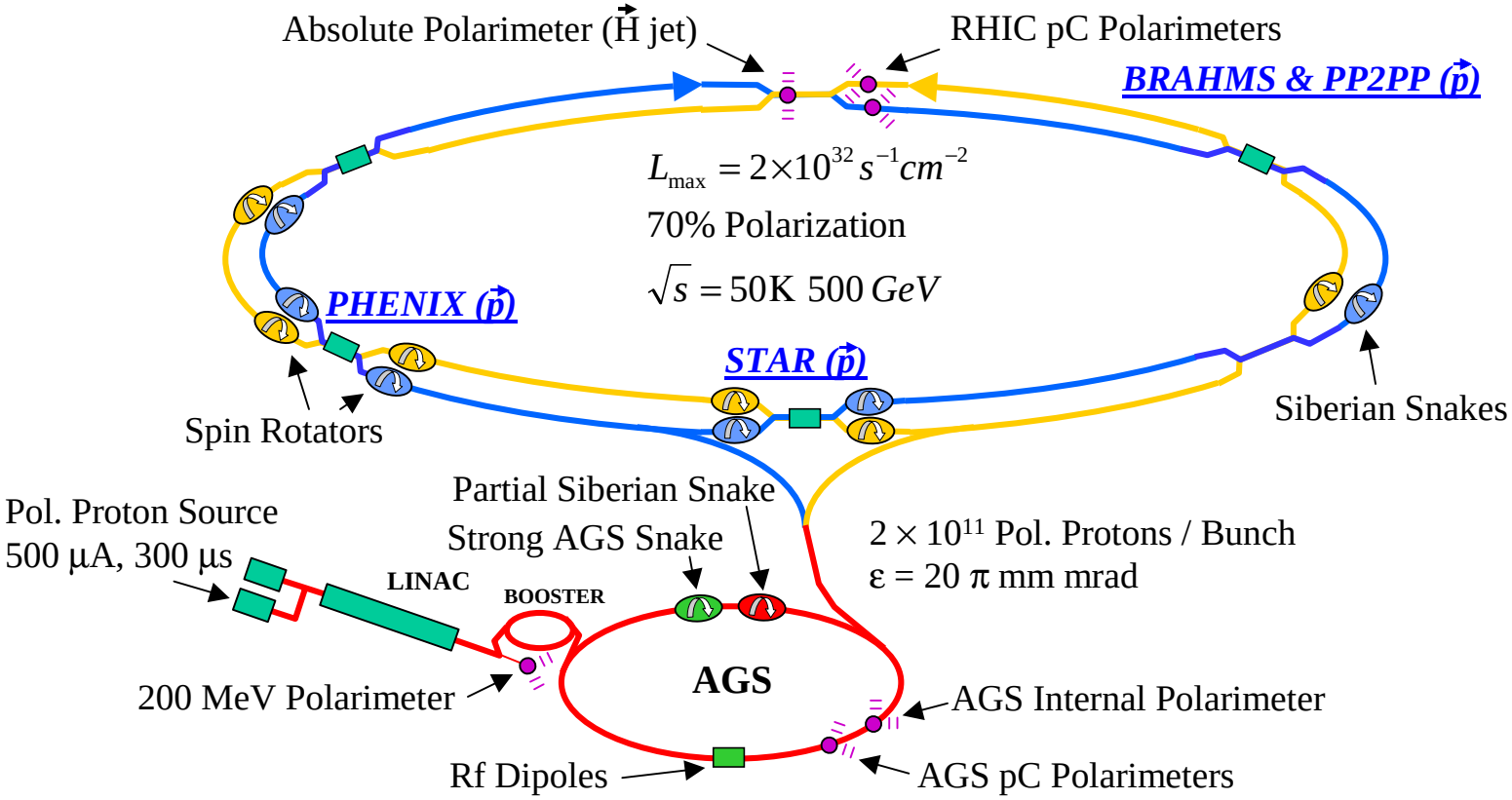
Quark-Gluon Compton scattering

$$\vec{p} + \vec{p} \rightarrow \gamma\,(+\,jet) + X$$

STAR

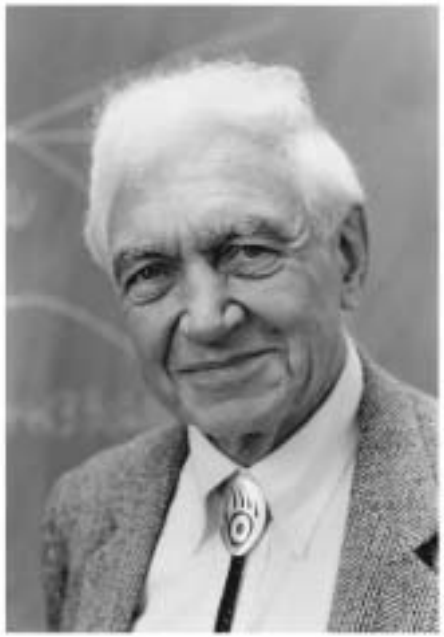


Polarized Proton Collisions in RHIC



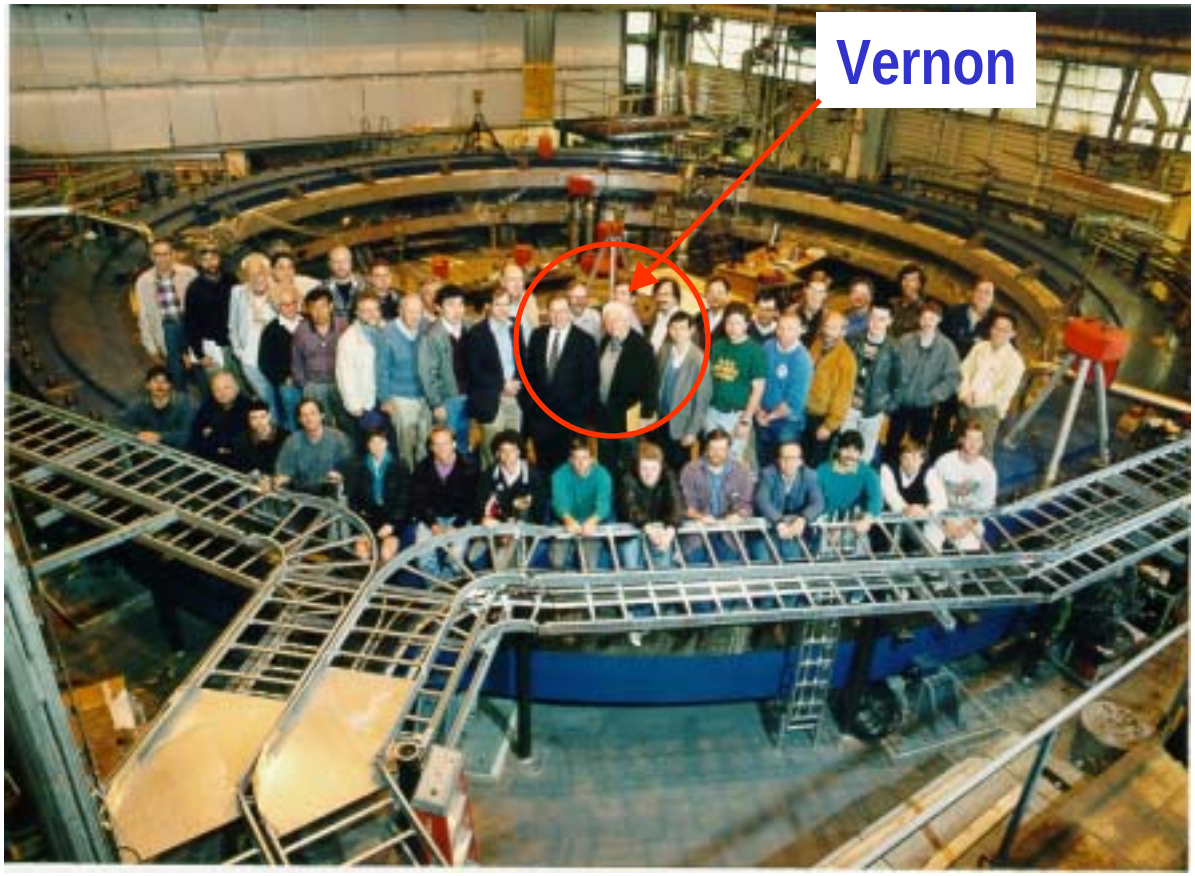
- **First colliding beams of polarized protons achieved in 2002**
- **First data with longitudinally polarized beams (spin rotators) in 2003**
- **Full Spin capability for machine and detectors will ramp up through 2005**

A brief aside… Vernon Hughes at BNL

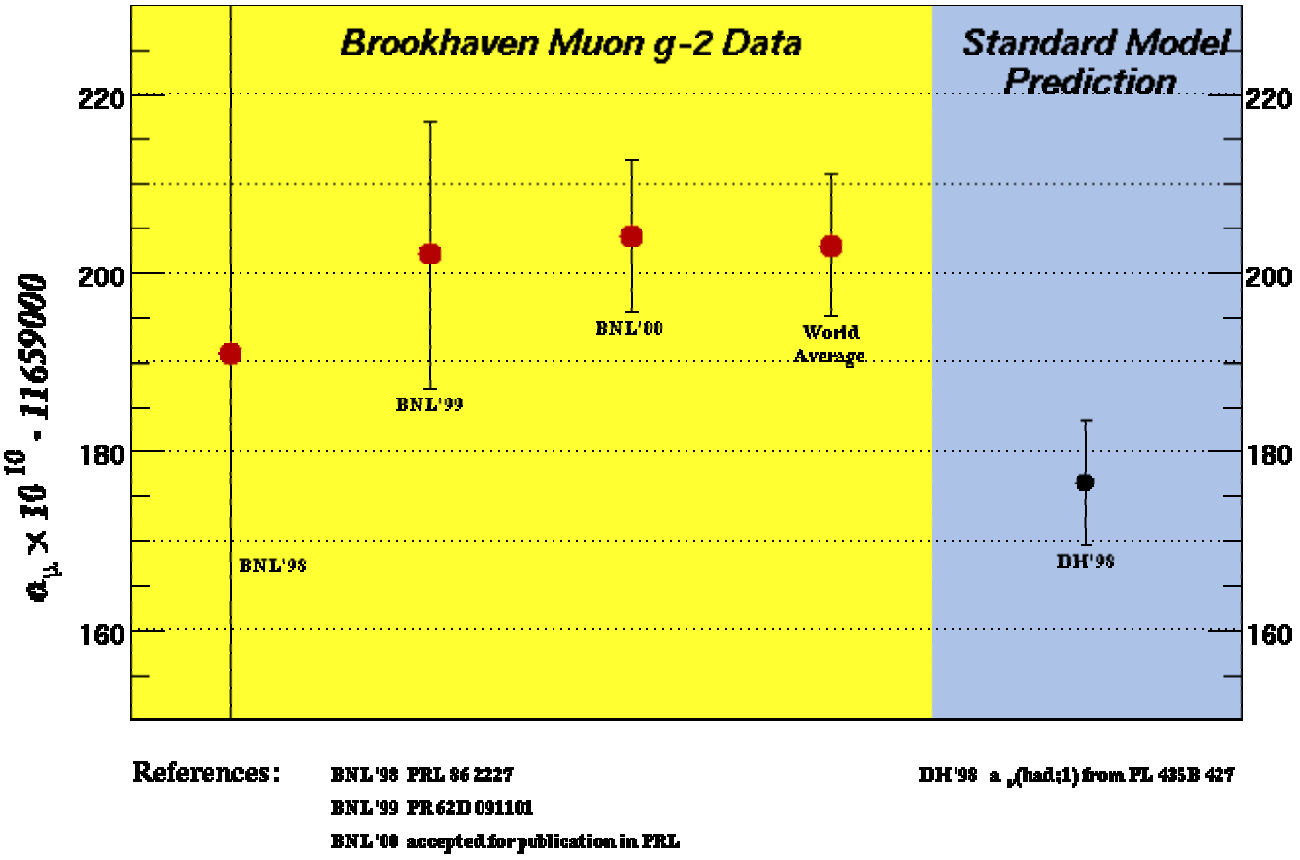


A pioneer in the development of spin-polarized beams, targets, and fundamental research at many labs around the world, Vernon was actively involved in the implementation of Spin capability in the RHIC collider– and was a leader in developing plans for the future electron-ion collider eRHIC.

The Muon G-2 Experiment at BNL



PRL **89** 101804 (2002)



"A sum rule for present physics" V. Hughes

Are we seeing QGP at RHIC?

First question: do we have "Matter" at high energy density?

✓ Strong collective interaction; local kinetic equilibrium…

Large volume compared with mean free path?

Anisotropic Flow

Is it quarks and gluons?

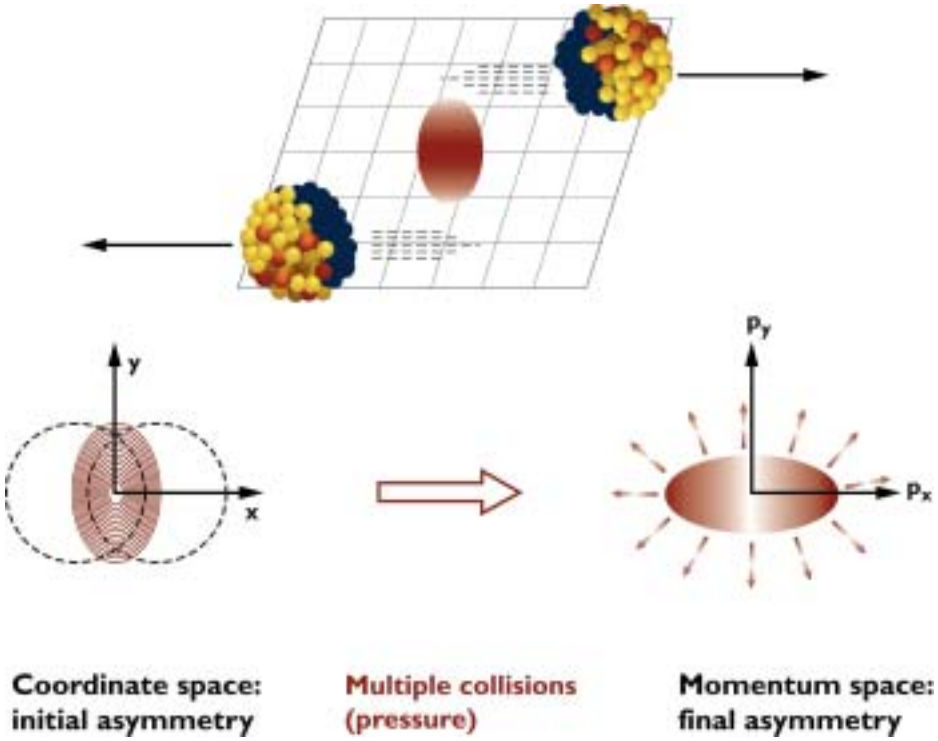
✓ Temperature and energy density well above critical values?

- Strong collective interaction at very early times?
- Color screening in dense phase?
- Opaque to jets?

Is there a phase transition?

- Chiral symmetry restored (shifted ρ mass)?
- Lattice predictions for the equation of state (latent heat)?
- Fluctuations near phase boundary?

Elliptic (anisotropic) Flow– Direct measure of collective interaction



A "barometer" that probes early-time thermalization

Momentum anisotropy w.r.t. the reaction plane:

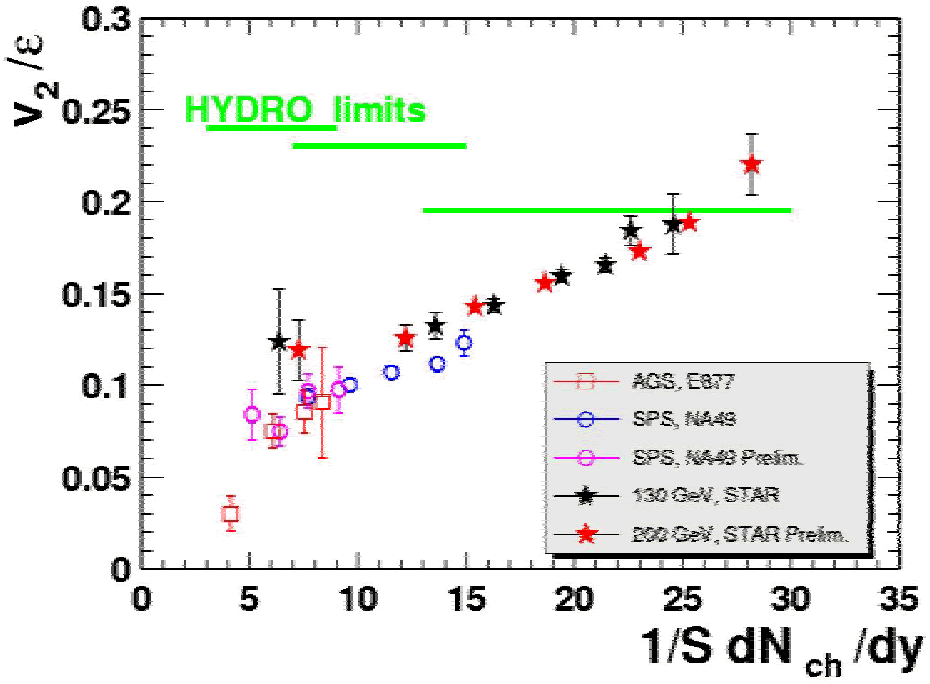
Interactions among constituents generate a pressure gradient, which transforms the initial coordinate space anisotropy into a momentum space anisotropy (no analogy in pp)

Directed Flow

Elliptic Flow

$$\frac{d^3N}{dp_t\,dy\,d\varphi} = \frac{d^2N}{dp_t\,dy}\frac{1}{2\pi}(1+2v_1\cos(\varphi)+2v_2\cos(2\varphi)+\ldots)$$

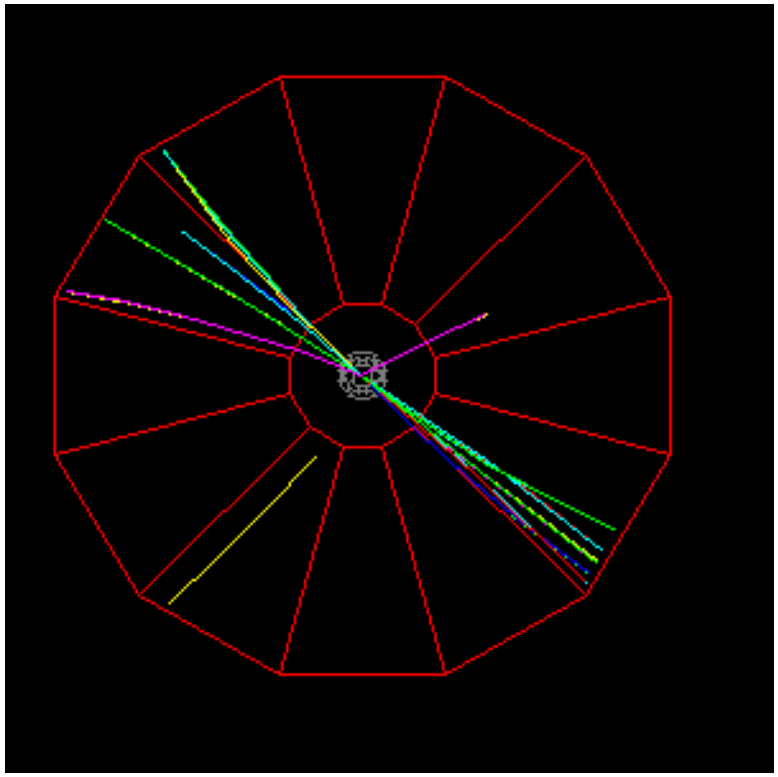
Measured elliptic flow vs. charged particle density



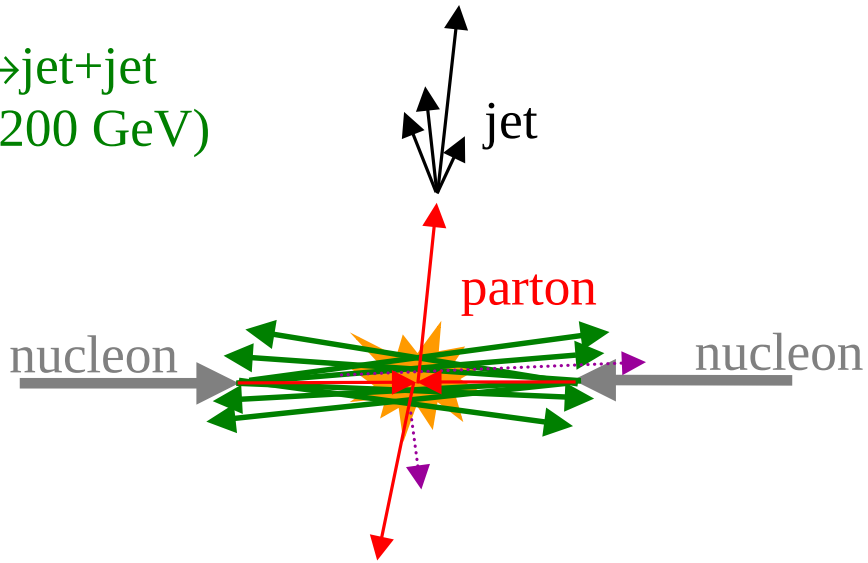
For RHIC collisions with highest particle density in the overlap region: Elliptic flow approaches the hydrodynamic limit

Hard Scattering at RHIC

cross sections are high!

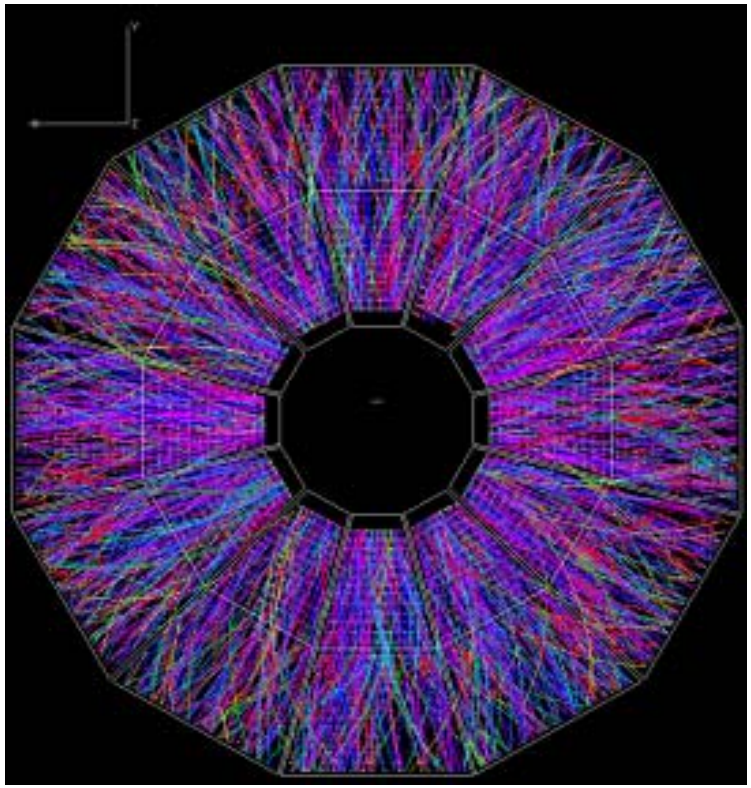


p+p →jet+jet
(STAR 200 GeV)



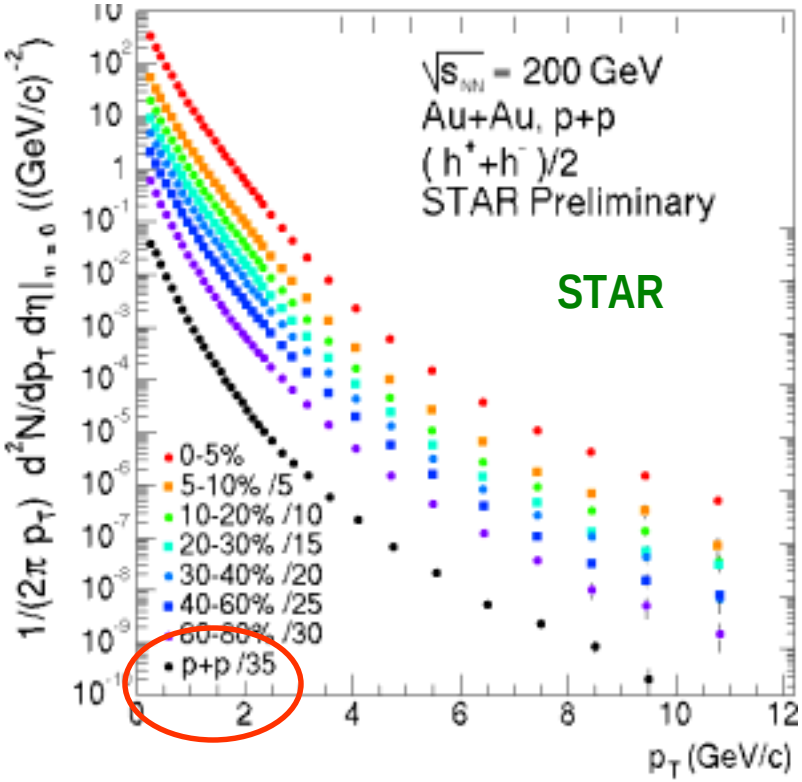
Au+Au →???

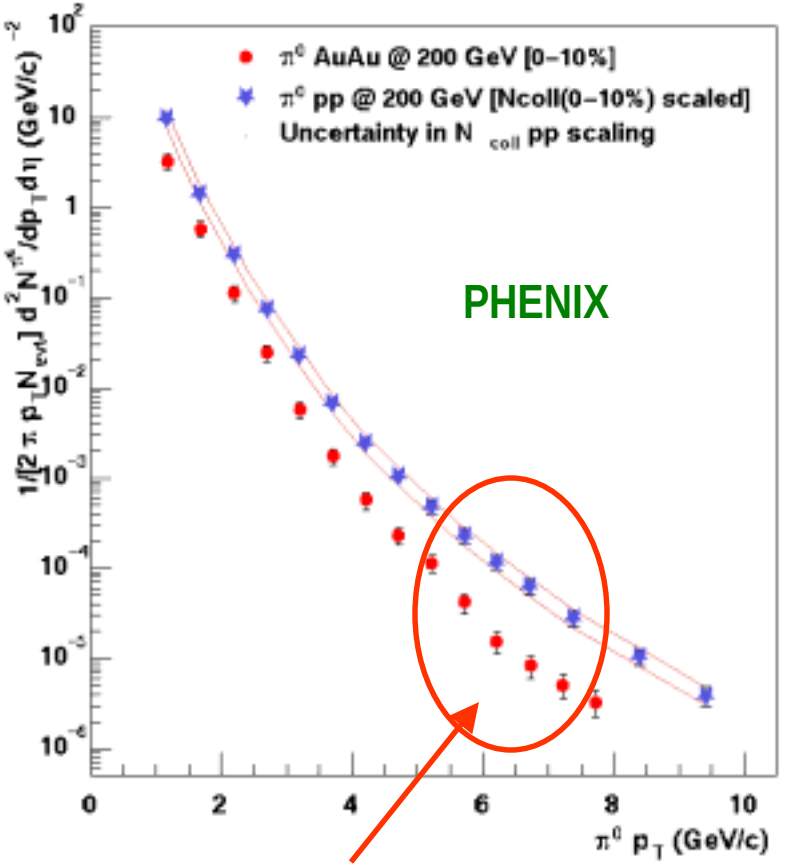
(STAR 200 GeV/nucleon)



High P_t Data

Well measured, as function of centrality, to p_t > 10 GeV/c.
Calibration data from p – p collisions in the same detectors.

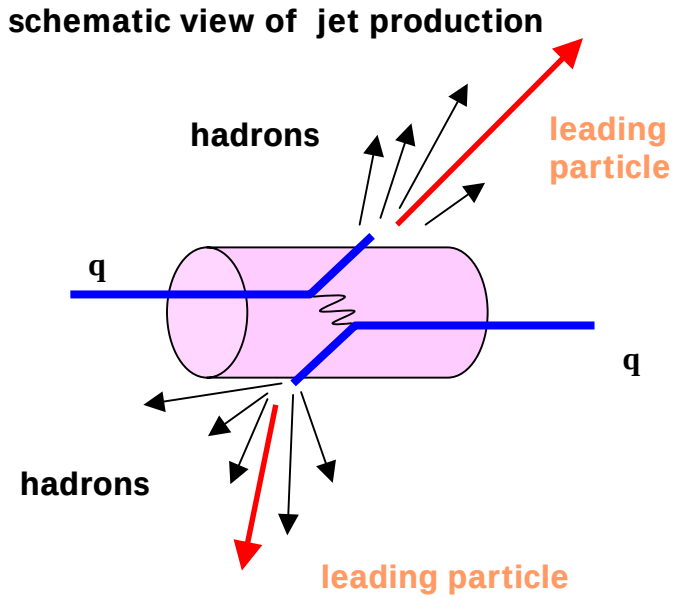




Clear suppression in central Au-Au relative to p – p at large p_t

Jet Quenching?

- Hard scatterings in nucleon collisions produce jets of particles.
- In the presence of a color-deconfined medium, the partons strongly interact (~GeV/fm) losing much of their energy via gluon Bremsstrahlung.
- "Jet Quenching"… strong dependence of ΔE on gluon density

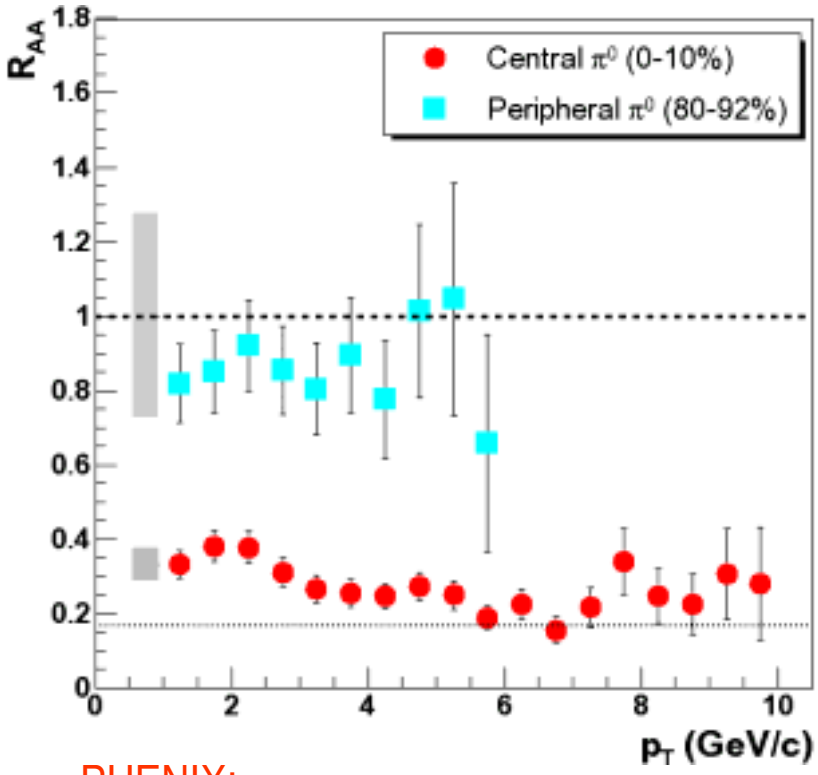


See: M. Gyulassy, I. Vitev, X.N. Wang, B.W. Zhang, "Jet Quenching and Radiative Energy Loss in Dense Nuclear Matter", published in *Quark Gluon Plasma 3*, R.C. Hwa and X. N. Wang, editors, World Scientific, Singapore, 2003.

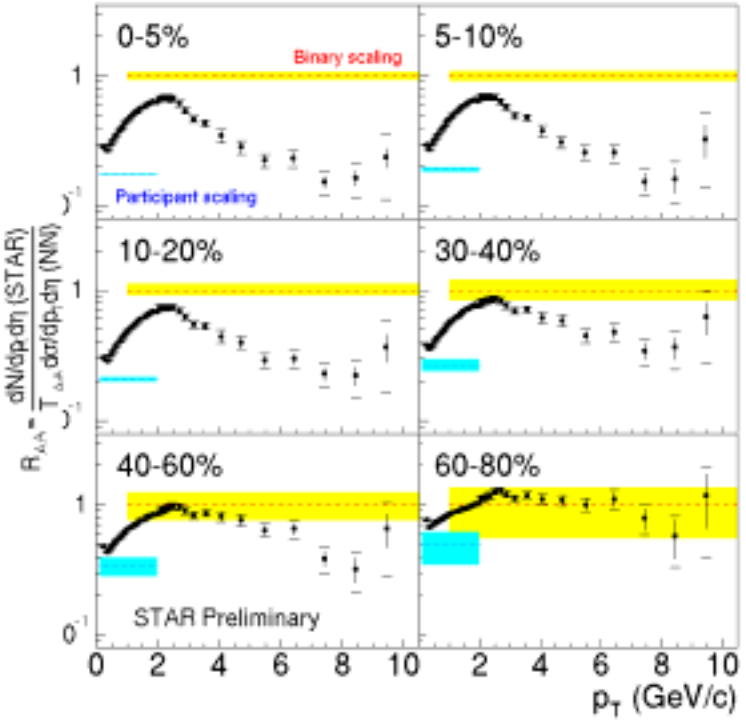
Suppression of leading hadrons in RHIC data

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

$\sqrt{S_{nn}}$=200: Au+Au

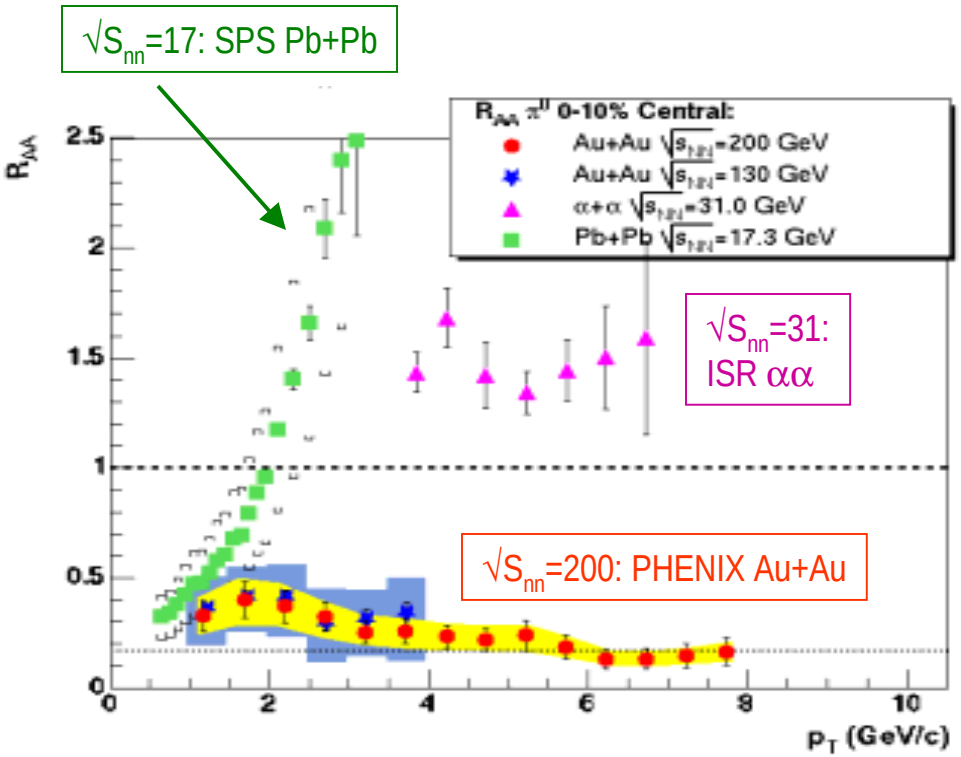


PHENIX:
Inclusive π^0 in central & peripheral collisions



STAR Charged hadrons:
Dependence on centrality

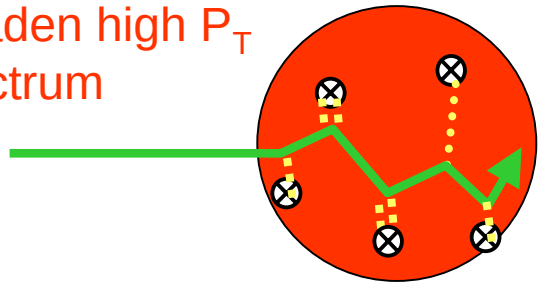
From SPS to RHIC: A major qualitative change at high p_t



Inclusive π^0 in central collisions

Cronin Effect:

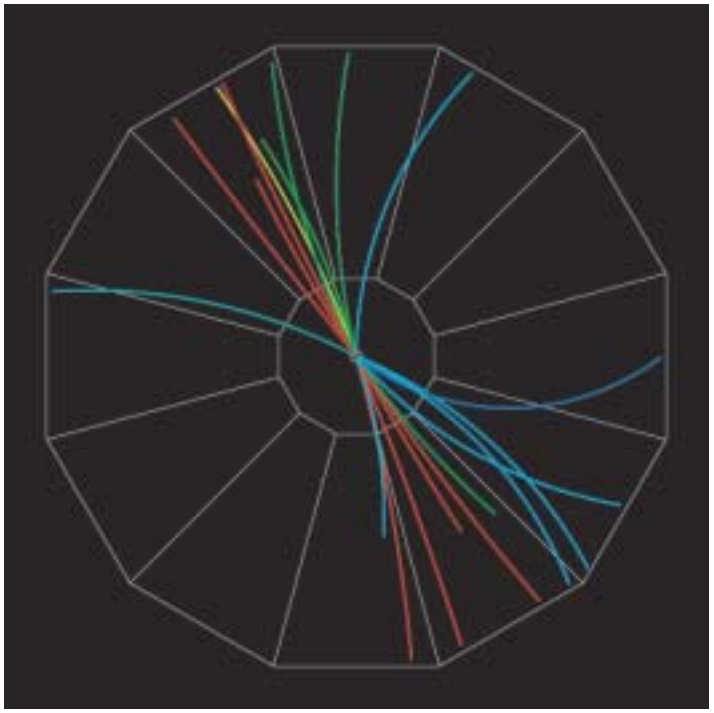
Multiple Collisions broaden high P_T spectrum



A recent survey of Cronin effect in proton-nucleus collisions: A. Accardi, hep-ph/0212148.

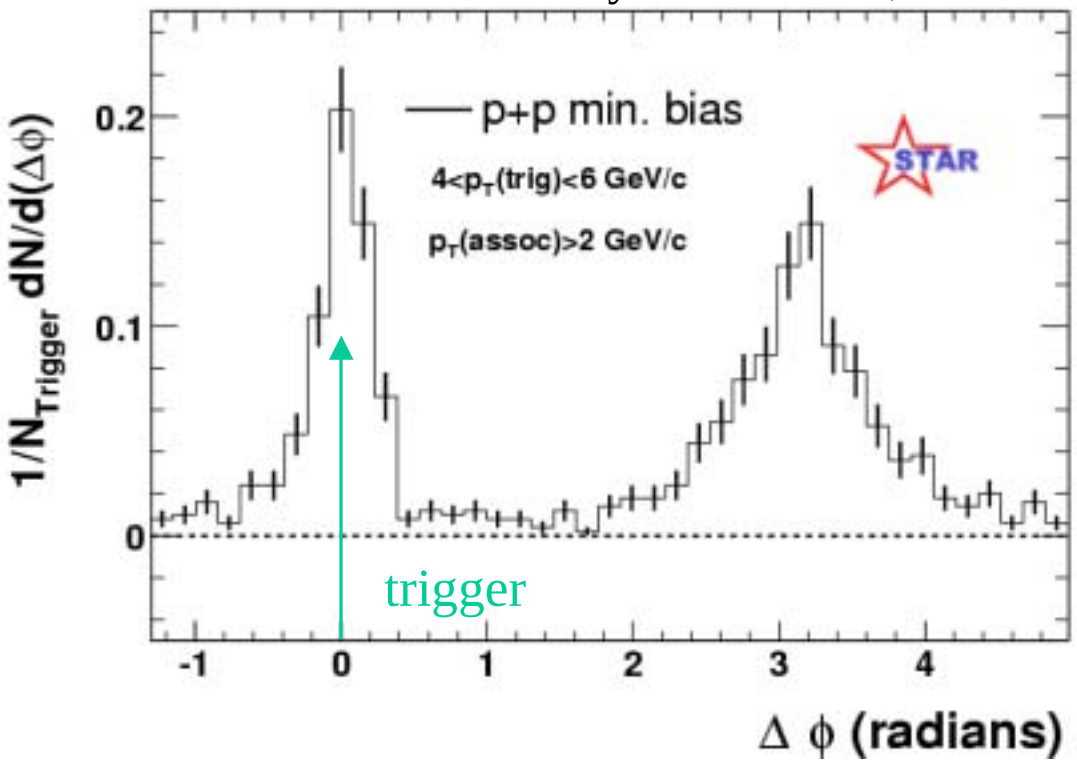
Jets and two-particle azimuthal distributions

p+p → dijet



- trigger: highest p_T track, p_T>4 GeV/c
- $\Delta\phi$ distribution: 2 GeV/c<p_T<$p_T^{trigger}$
- normalize to number of triggers

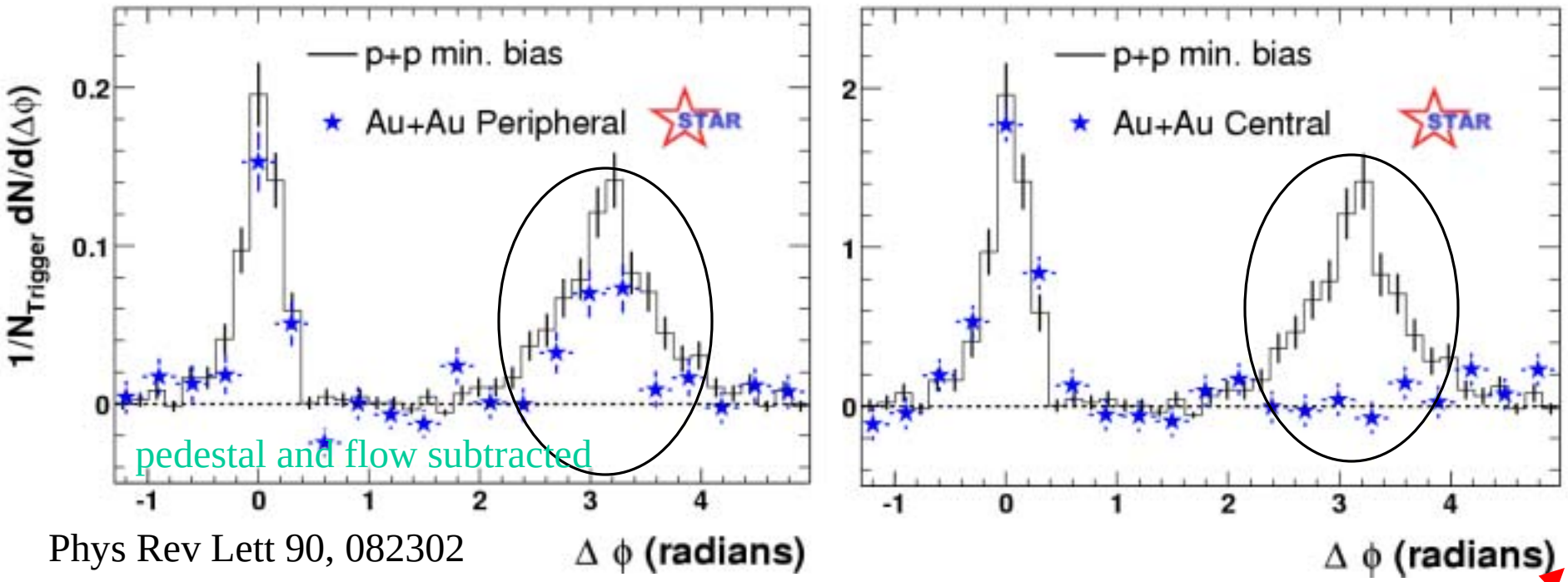
Phys Rev Lett 90, 082302



Azimuthal distributions in Au+Au

Au+Au peripheral

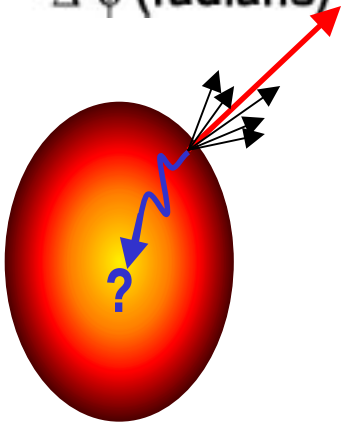
Au+Au central



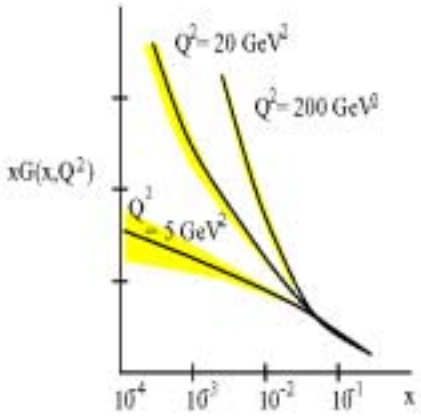
Phys Rev Lett 90, 082302

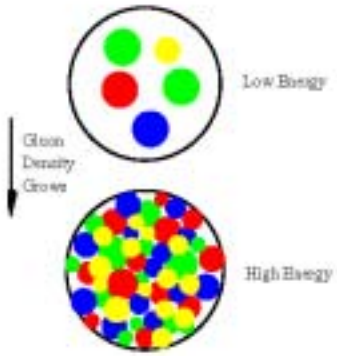
Near-side: peripheral and central Au+Au similar to p+p

Strong suppression of back-to-back correlations in central Au+Au



Gluon Saturation and Color Glass Condensate





Gribov, Levin, Ryskin;
Mueller, Qiu
McLerran, Venugopalan

Gluon phase space density per unit area:

$$\rho = \frac{1}{\pi R^2}\frac{dN}{dp_T^2}$$

until

$$\rho \sim 1/\alpha_{strong}$$

$$Q_{sat}^2 \sim \int d^2k_T\ \rho$$

$$Q_{sat} >> \Lambda_{QCD}$$

implies

$$\alpha_{strong} << 1$$

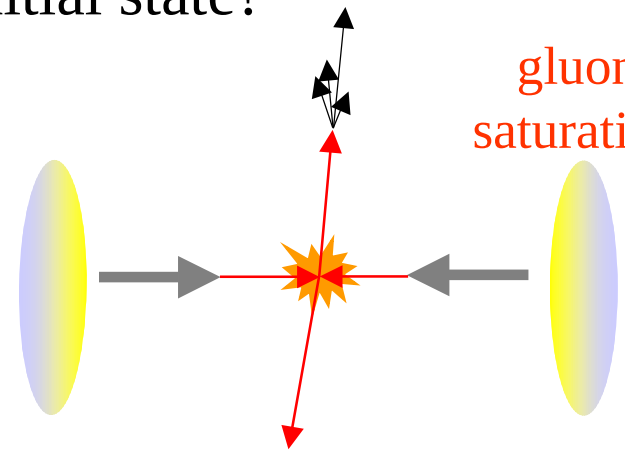
A new, emerging view of AA physics:
Not everything happens in the final state… "A lot of action is going on even before the nuclei collide" *(Kharzeev, McLerran & Co.)*

In this picture … Jets are not quenched, but are *a priori* made in fewer numbers due to saturation of initial-state gluon density.

Is suppression an initial or final state effect?

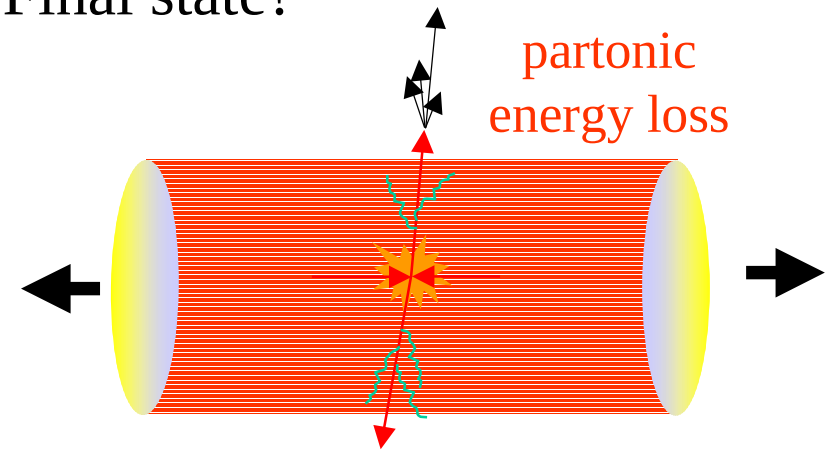
Initial state?

gluon saturation

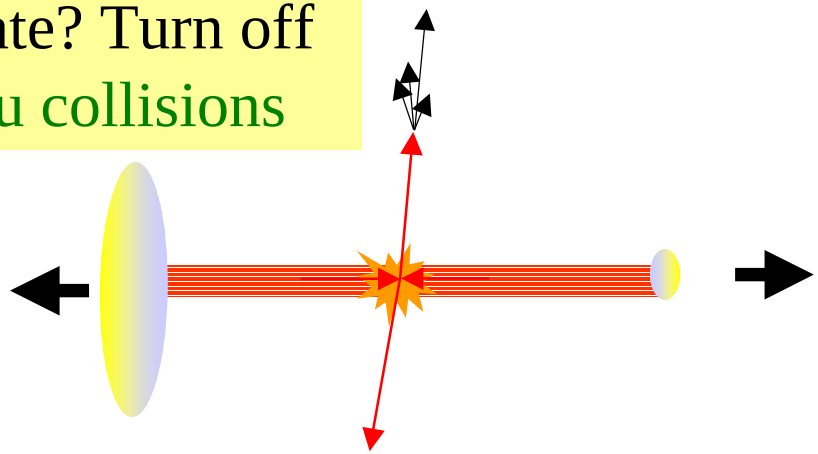


Final state?

partonic energy loss

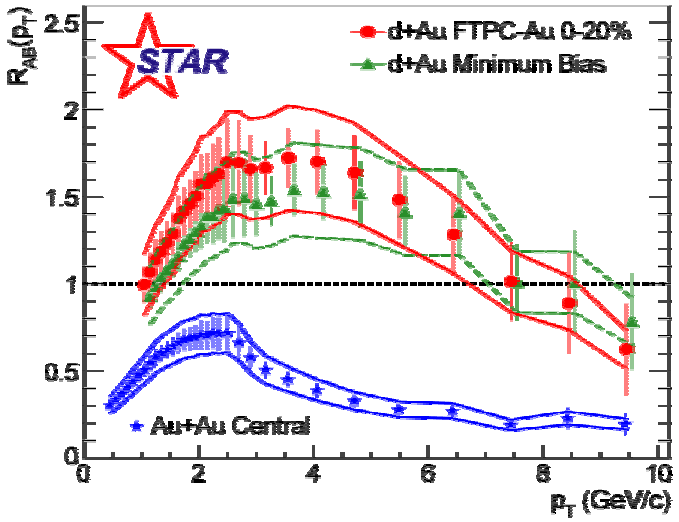


How to discriminate? Turn off final state ⇒ d+Au collisions

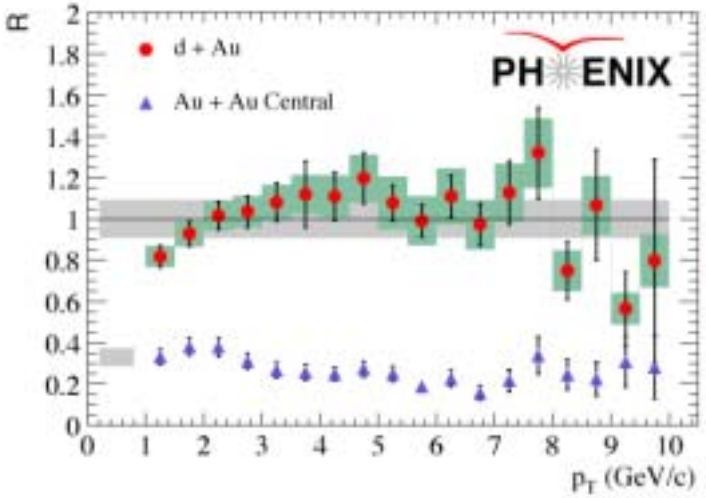


The verdict is in…

Deuteron-gold data at $\sqrt{S_{nn}}$ = 200 GeV recorded Jan – Mar 2003

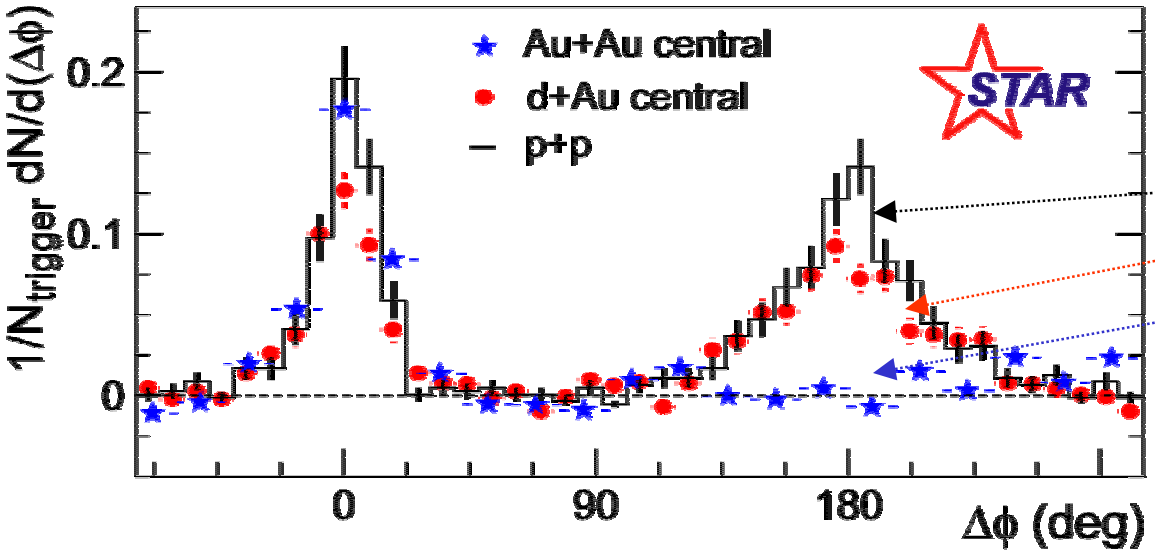


STAR charged hadrons



PHENIX pi-zeros

Phys. Rev. Lett. **91**, Aug. 2003
nucl-ex/0306021 (PHENIX); nucl-ex/0306025 (PHOBOS);
nucl-ex/0307003 (BRAHMS); nucl-ex/0307007 (STAR)



Recoil jet peak:

p – p

Central d – Au

Central Au - Au

The data indicate a hot, dense medium of final state particles that is characterized by strong collective interactions at very high energy densities.

Are we seeing QGP at RHIC?

First question: do we have "Matter" at high energy density?

- Strong collective interaction; local kinetic equilibrium…
  Large volume compared with mean free path? } ..... **Yes**

Is it quarks and gluons?

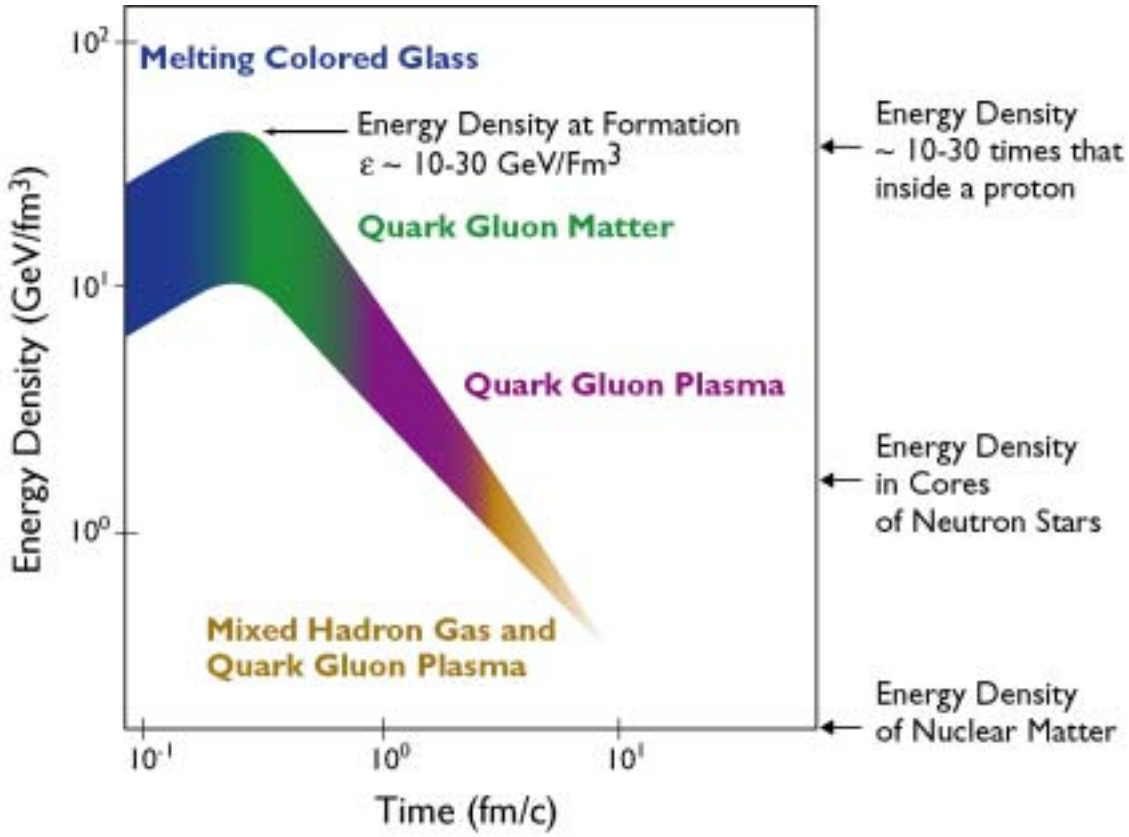
- Temperature and energy density well above critical values? ..... **Yes**
- Strong collective interaction at very early times?
- Color screening in dense phase?
- Opaque to jets? ..... **Yes**

Is there a phase transition?

- Chiral symmetry restored (shifted ρ mass)?
- Lattice predictions for the equation of state (latent heat)?
- Fluctuations near phase boundary?

There is a lot more to learn, but at this point it appears that the answer is **Yes.**

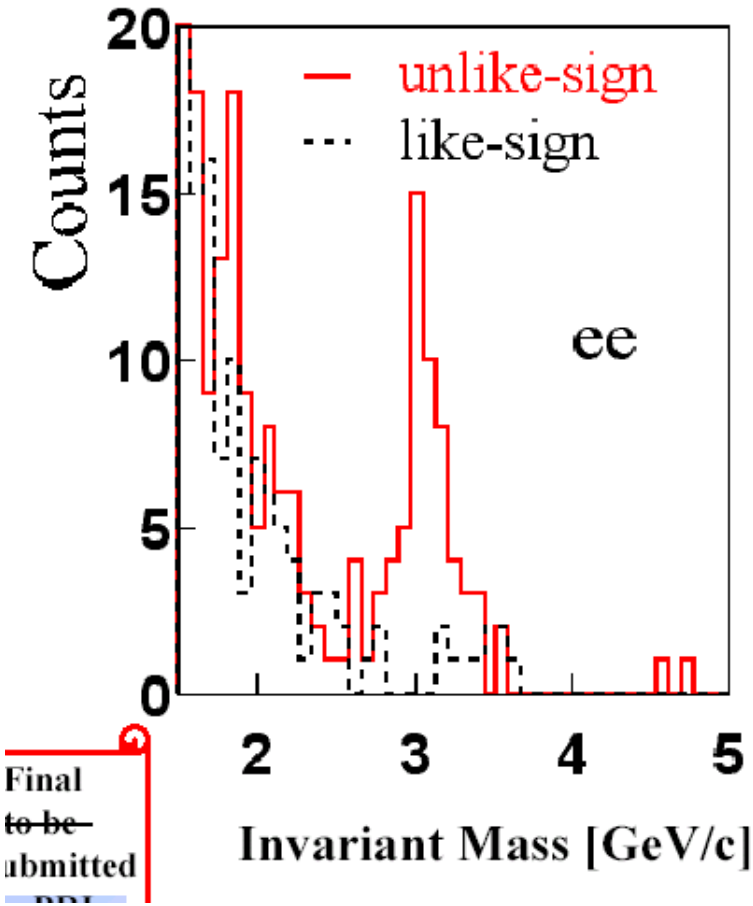
The Emerging Picture

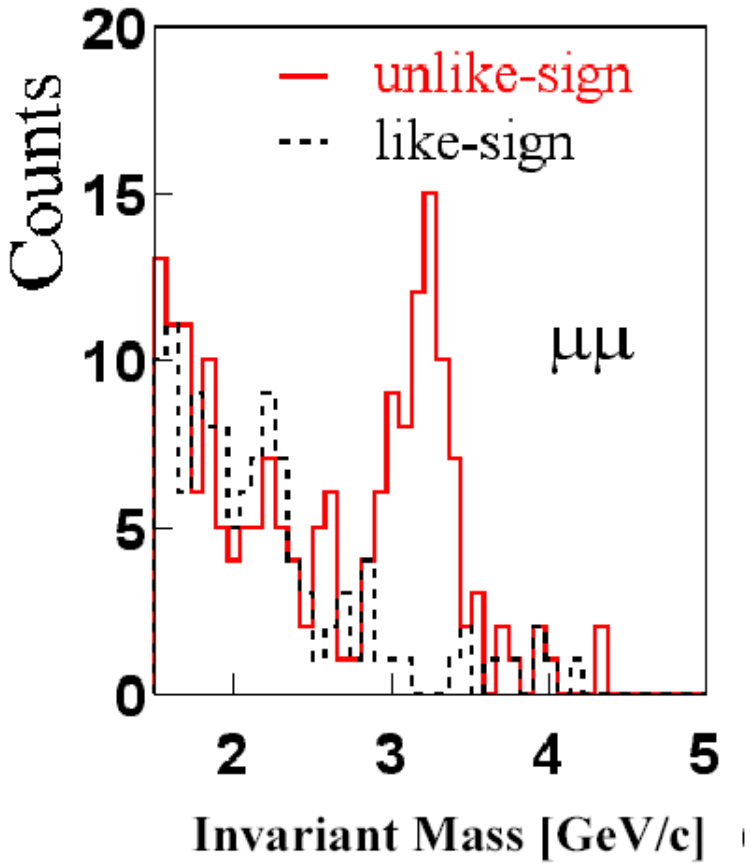


Estimates of energy density vs. time during the evolution of a collision.

Predicted sequence of states of QCD matter.

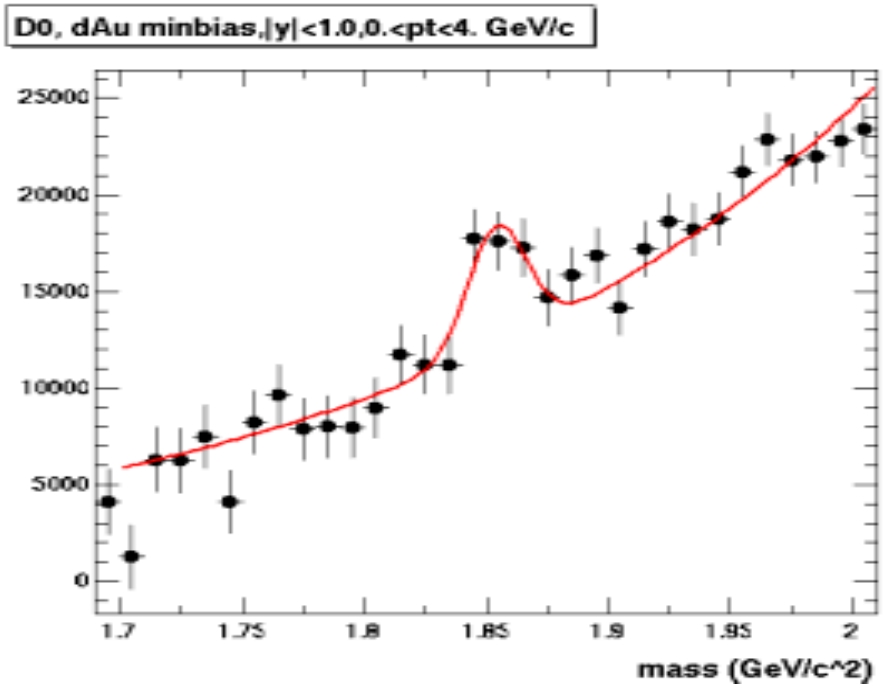
Soon to come… J/ψ (PHENIX)

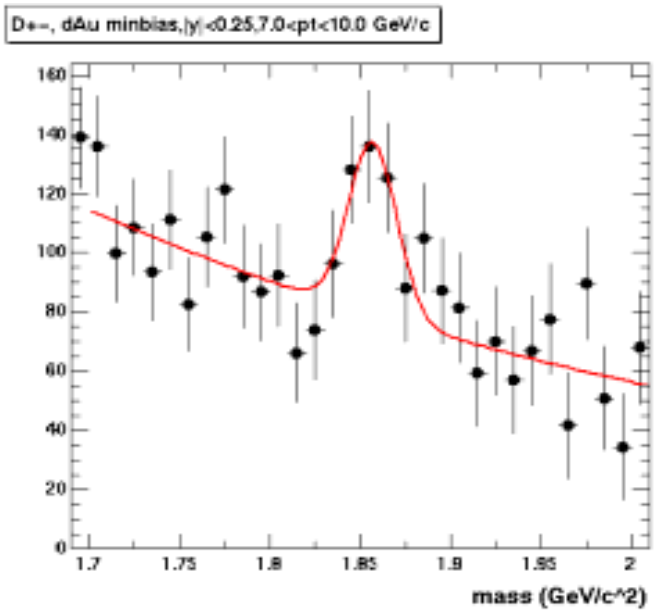




Final
~~to be~~
ubmitted

Soon to come… open charm (STAR)





Deuteron-Gold data

Measurements Beyond the Initial Exploratory Phase

Extended machine & detector capability at RHIC

High P_t and Q^2:

- Direct photons to P_t > 15 GeV/c
- Photon-tagged jets…*jet tomography*
- Low x, high Q^2 in pA… *Probe color glass*

Rare probes:

- Many x1000 upsilons
- W production in AA pA pp

Very large unbiased event samples:

- Open Charm and Beauty
- Low mass lepton pairs… ρ mass spectrum
- Low **P_t Direct Photons** } Direct EM radiation from plasma
- γγ interferometry…
- Disoriented Chiral Condensate; Strong CP violation

A new regime of yet higher energy density at LHC